White Paper

River Restoration and Fluvial Geomorphology

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River Restoration and Fluvial Geomorphology

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Development of a Guidelines Document for Streambank Stabilization and
Natural Stream Channel Design (DES #B-04-SW-11)

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1.0 INTRODUCTION

> *"We may conclude then that in every respect the valley rules the stream. Its rock determines the availability of ions, its soil, its clay, even its slope. The soil and climate determine the vegetation, and the vegetation rules the supply of organic matter. The organic matter reacts with the soil to control the release of ions, and the ions, particularly nitrate and phosphate, control the decay of the litter, and hence lie right at the root of the food cycle." (Hynes, 1975)*

River corridors and their watersheds are integrally linked, as embodied in the above statement by H.B. Hynes, "the father of running water ecology." Furthermore, the interrelated physical, chemical, and biological components of aquatic ecosystems are a function of their valley position and watershed condition. Rivers transport water and sediment in a dynamic equilibrium (Lane, 1955) from erosional headwaters, through mid-order transfer zones, to downstream locations where sediment is deposited. The understanding of the most likely states in river patterns and processes via the study of fluvial geomorphology has led to a multitude of ways to measure and classify channels. This discipline is rapidly expanding as researchers and practitioners look to further understand a river's most probable state and use this information to more effectively manage flowing waters at appropriate spatial and temporal scales.

The management of river systems has deep historic roots due to persistent human use of this resource for a variety of services such as transportation, food, water, mechanical energy, and waste disposal. These valuable benefits provided by flowing waters brought humans to live very close to the banks of rivers, and thus caused conflicts between humans and natural forces in river corridors and their extended floodplains. Early ad hoc management of river channels led to more regimented efforts of actions that seemed to always work against natural river processes. The end result is frequently mismanagement cycles where common changes to river corridors actually exacerbate the exact problem that was trying to be avoided. Needless to say, this has led to costly, long-term commitments to managing rivers in addition to increased risk to human investments. In the northeast United States, historic changes to river corridors and watersheds have disrupted natural form and processes and often lead to increased channel instability, reduced water quality, and the impairment of aquatic habitat.

The growing movement of managing and restoring rivers to return as much natural processes as allowable with the current watershed condition seems an appropriate next step to end centuries of degraded river systems. It is imperative that one understands the expected biophysical state of the river based on valley characteristics, so that restoration implementation can incorporate holistic thinking regarding altered current watershed and river corridor state and processes. Only then can projects have a high chance for success, which often includes the over-arching goals of both protecting human investments in river corridors and maintaining healthy aquatic habitat. Project goals such as self-sustaining resiliency, the ability to monitor improvements, improvements spanning the various components of the aquatic ecosystem, and the maximization of the allowable natural processes will help design and application. These concepts are an important addition to the traditional engineering-based toolbox of the river restoration practitioner. As river restoration project planning has evolved, so to have the principals of design. The river restoration community seems to be at a critical crossroads where engineers, fluvial geomorphologists, aquatic biologists, and others are coming together to try and move towards standard design methodologies and monitoring protocols. Differences between virtually every project site inevitably eliminate a one-size-fits-all design template, yet standardization of the design protocols based on problem identification, river type, corridor condition, watershed scenario, and primary project objectives will help move the practice of river restoration forward, closer to a truly natural process approach.

This document constitutes a white paper prepared for the New Hampshire Department of Environmental Services (DES) summarizing findings from a literature review on topics related to natural channel design and streambank stabilization, with an emphasis on fluvial geomorphology. Chapter 2.0 is a review of natural river processes and the basic principals of fluvial geomorphology. Chapter 3.0 is a discussion of the alteration of river corridors and watersheds and how river form and process are affected. Chapter 4.0 contains an overview of planning and implementing natural channel design and streambank stabilization projects. Chapter 5.0 contains additional information that is useful for understanding natural river processes and restoration in the climatic and geophysical setting in the State of New Hampshire. Although a comprehensive review of each and every aspect of these topics is beyond the scope of this document, the white paper presented here offers an overview of topics important to the restoration of rivers. During the literature review we selected what we believe to be the most important references that either originally establish a topic, offer general concept descriptions, present advanced technical theory, are useful for application, and present recent significant research. The documents in this library (Appendix A) afford the reader the finer details to build on the central concepts presented here. In addition, we present an annotated bibliography of existing manuals covering natural channel design, streambank stabilization, general river restoration technical information, roadways and river corridors, monitoring, and qualitative reports and policy papers pertaining to river restoration (Appendix B). The compelling aspects of the many existing manuals that are regularly used in modern river restoration work will be drawn upon as we move forward towards establishing a guidelines document for streambank stabilization and natural channel design for the State of New Hampshire.

2.0 NATURAL RIVER FORM AND PROCESSES

"It is the purpose of this discussion to demonstrate the importance of both time and space to the study of geomorphic systems." (Schumm and Lichty, 1965)

2.1 Introduction

In reviewing river restoration literature and existing design aids, there is a common reoccurring theme of improving physical natural form and processes of a river. Form, or shape, of a river channel can be measured using a suite of geomorphic variables in the lateral, longitudinal, and vertical directions relative to the flow of water. Process, the functions a river performs, is more difficult to observe and measure yet may be investigated based on known patterns and empirical relationships garnered from many observations in a variety of river systems. In this chapter, we review some basic concepts of fluvial geomorphology that are essential to proper planning, design, and implementation of river restoration projects – scale, dynamic equilibrium, common variables, channel classification, and channel evolution. The physical components of a river are integrated with the chemical and biological aspects of aquatic ecosystems, and together determine the quality of habitat. Finally, human dimensions often play a central role in virtually all aspects of river restoration projects.

2.2 Spatial and Temporal Scales

2.2.1 Spatial Scales

The features of a river system have been described in a spatial hierarchy (Frissell et al., 1986) ranging from a watershed down to a particle on the streambed (Figure 2.1). At the largest scale, watersheds integrate all surface water in an area and transport that runoff to an outlet via a network of channels that sit in valleys. Channels are frequently described in homogenous longitudinal segments called reaches. Large watersheds are typically referred to as basins whereas small watersheds are frequently called catchments. Within

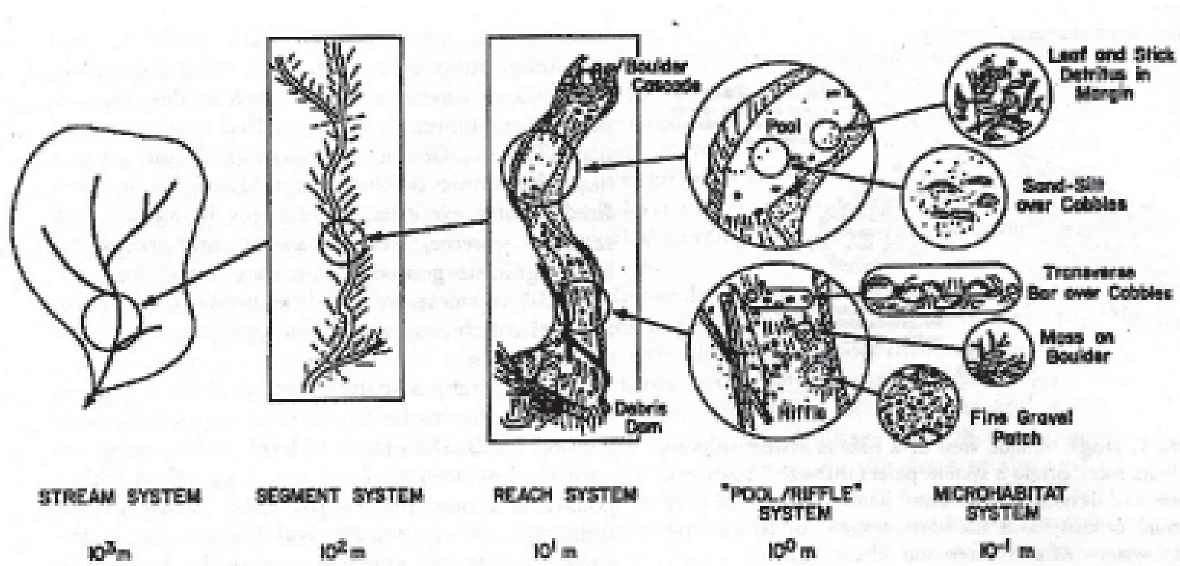


Figure 2.1: The spatial scales of stream features in a watershed framework (Source: Frissell et al., 1986).

watersheds, valleys make up the largest geophysical features and consist of walls and floors. The floors of valleys contain the river channel and its floodplain when present – collectively termed the river corridor. It is in the valley bottoms that fluvial processes take place. Within the channel, geomorphic features such as a riffle or pool identify smaller units indicative of local hydraulics and instream habitat. Decreasing spatial scale further, individual particles such as boulders and cobbles are the important habitat components. Due to the fact that natural river processes take place across each of these lateral, longitudinal, and vertical spatial scales, river restoration should be conducted with consideration of the hierarchies of spatial scale. Such holistic planning and design will generate the best projects that incorporate the appropriate scales of degradation and restorative actions. "Researchers often answer questions that are relevant over small spatial and short temporal scales, but these may be only weakly linked to the problems at larger spatial and longer temporal scales that managers must address" (Fausch et al., 2002).

The spatial extent of river-landscape interactions may extend beyond the watershed divide and to the boundary of the contributing groundwater aquifer in some systems. Recharge is an important process in maintaining adequate baseflow and cool temperatures during low-flow periods in temperate regions. The exchange of groundwater to rivers via upwelling (i.e., hyporheic exchange) has been shown to be an important habitat feature for fish and macroinvertebrates (Boulton et al., 1998). River restoration activities may thus need to consider processes that originate outside the project watershed.

2.2.2 *Temporal Scales*

Due to the dynamic nature of flowing waters, the characterization and restoration of river systems is only complete upon inclusion of temporal scales (White and Walker, 1997). From pulses of water or sediment moving down a river that can vary on the order of minutes, to the rise and fall of discharge associated with a single storm event that fluctuate in hours or days, all the way to inter-annual flow variability due to climate differences, channels are shaped by their temporal character. The flow discharge, or rate at which a unit volume of water moves past a location in a unit time, is the master variable in rivers influencing every aspect of the aquatic ecosystem. As spelled out by the continuity equation ($Q = V * A$), an increase in discharge (Q) is typically accompanied by an increase in water velocity (V) and wetted cross-sectional area (A). However, the influence of discharge across the aquatic ecosystem extends beyond a change in wetted area. Sediment transport rates, nutrient loads, hydraulic patterns, and area of useable aquatic habitat exemplify variables that are all largely a function of flow. Effective restoration needs to consider the full range of flow and associated temporal dynamics at a project site, reach, and watershed.

2.2.3 *Dynamic Equilibrium*

A river moves water, sediment, and debris from uplands to lowlands. As part of the hydrologic cycle, flowing waters constitute the transport of freshwater runoff back to the ocean. With this runoff comes the movement and shaping of inorganic particles from terrestrial environments to the coastal ocean. Through this process, river valleys are maintained. Early canal engineers (Lacey, 1930) identified the regime concept where channels are in equilibrium without long-term scour or deposition. Lane (1955) expanded upon this theory of dynamic equilibrium between water and sediment in river channels where the product of discharge and channel slope is proportional to the product of sediment discharge and the median particle size (Figure 2.2). This relationship has emerged as a fundamental tool for investigating channel stability, and physical impairments observed in the field can frequently be traced back to deviations in the dynamic equilibrium between water and sediment.

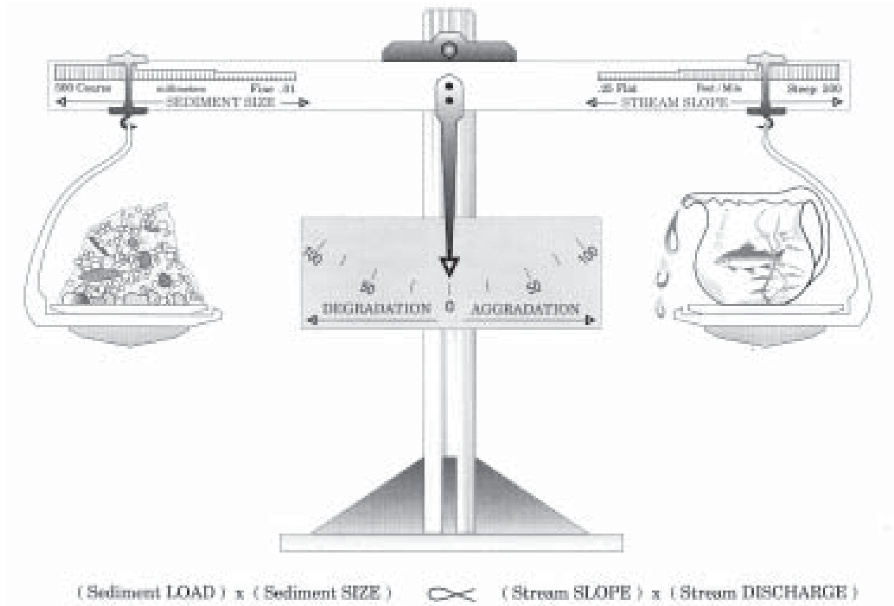


Figure 2.2: The dynamic equilibrium between sediment and water in stream channels (Source: Lane, 1955; Rosgen and Silvey, 1996).

2.3 Fluvial Geomorphology

The study of river form and process, fluvial geomorphology, has recently joined the disciplines of hydraulic engineering and aquatic biology as the main components of river assessment and restoration. Fluvial geomorphology is an off-shoot of geology focused on erosional landscapes (e.g., Davis, 1899; Horton, 1945), and is mostly field observation and measurement to identify, classify, and re-construct common patterns having desirable characteristics. Just as an engineering river restoration design guide manual contains theoretical equations and modeling approaches (e.g., Richardson et al., 2001), a geomorphology guide has photos of river types and empirical relationships of commonly measured variables (e.g., Rosgen and Silvey, 1996).

2.3.1 Geomorphic Variables

Geomorphic variables are used to characterize virtually every aspect of a channel (see Harrelson et al., 1994). Perpendicular to the direction of flow (Figure 2.3a), cross-sectional area, width to depth ratio, entrenchment ratio (i.e., width of the flood-prone area divided by the channel width), meander belt width, and valley width define the lateral characteristics from channel to valley wall. Along the direction of flow (Figure 2.3b), channel slope, sinuosity, meander wavelength, riffle spacing, and planform pattern exemplify

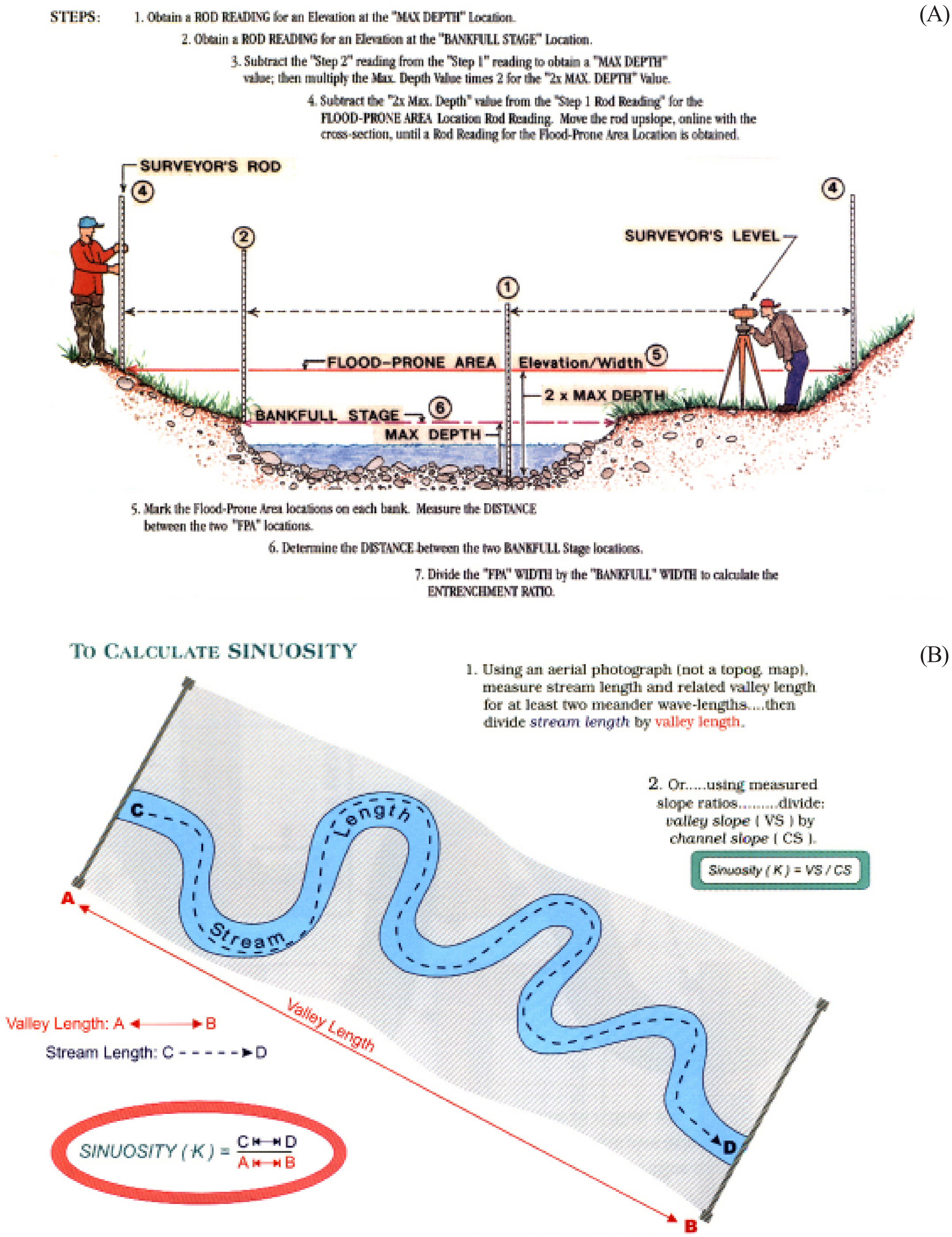


Figure 2.3: (A) A schematic of the measurement of bankfull width, bankfull depth, and flood-prone area at a stream channel cross-section to calculate entrenchment ratio. (B) A schematic of the measurement of stream length and valley length from a plan view of a stream reach to calculate channel sinuosity (Source: Rosgen and Silvey, 1998).

characteristics measured longitudinally along the river corridor. A description of sediment size, often in terms of median grain size (d_{50}), is typically included in geomorphic descriptions by either sieving fine material or performing a Wolman (1954) pebble count in the channel (Bunte and Abt, 2001) to explore the current sediment regime. In addition, flow velocity and instantaneous discharge are measured to get a snapshot of flow conditions, and possibly link to a nearby gauge.

Modern "hydraulic geometry relationships (HGR's)" are a simplified form of the regime equations developed in India and Pakistan for design of canals in equilibrium (Lacey, 1930), where neither net erosion nor deposition occurs over long periods of time. These power relationships are useful for approximating width, depth, and velocity at a given location in a river with known discharge or drainage area. Simons and Albertson (1960) presented regime equations for the United States that remain in use today where more local data is absent. Early HGR's (Leopold and Maddock, 1953) were created for channels within a single watershed; however, data for multiple rivers were eventually plotted together to form the first regionalized version of HGR's (i.e., regional curves). Regional curves have also been stratified by geomorphic river type and streambed sediment size (Rosgen and Silvey, 1996). Several states in the northeast U.S. have existing HGR's that are used for river restoration design (e.g., Appendix J, VTANR, 2004). The State of New Hampshire presently has provisional regional curves that are under development (Figure 2.4). Although widely used as design guides, recent research cautions against sole reliance on regional curves for river restoration. For example, the power relationship for width is influenced by the streambank material and vegetation type (Anderson et al., 2004). Wohl et al. (2004) showed that hydraulic geometry in mountain rivers was most strongly related to channel slope, not discharge. Caution is required when applying HGR's to disturbed streams, where most restoration design takes place, as the original HGR construct by Leopold and Maddock was for natural rivers (1953).

2.3.2 Dominant Discharge

Dominant discharge theory suggests that there is one flow that is most responsible for creating a channel's morphology, and that a channel that is designed using this dominant discharge should maintain itself in a stable form in dynamic equilibrium (FISRWG, 1998). The dominant discharge is used as a surrogate to describe the flow that transports the most sediment over the long term (i.e., the effective discharge), since the latter requires a lot of equipment and time for measurement in the field. Wolman and Miller (1960)

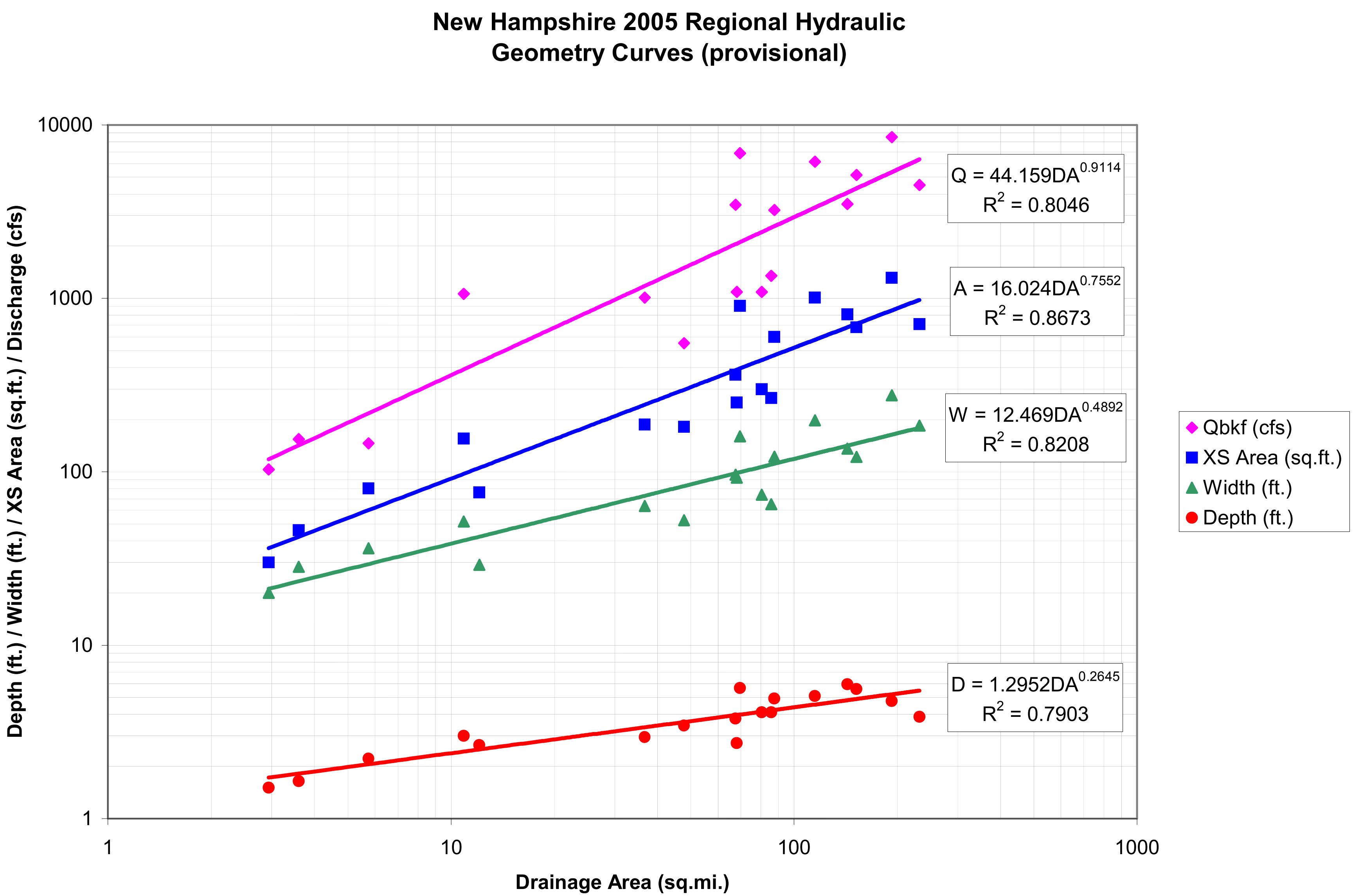


Figure 2.4: Provisional regional hydrualic geometry curves for the State of New Hampshire (Source: The New Hampshire Stream Team, 2005).

showed that the dimension and shape of a meandering channel are more closely linked to small, frequent storms occurring every 1.5 ($Q_{1.5}$) years rather than to more rare larger flows. In addition, $Q_{1.5}$ was found to be equal to the bankfull flow (Q_{bf}) for many rivers (Wolman and Miller, 1960). This finding presumably further simplified the use of dominant discharge theory for design purposes as now a field indicator could be used to identify the channel forming discharge where sediment transport and hydrologic data are absent. It turns out that the use of $Q_{1.5}$ and Q_{bf} are at the center of the debate as to whether a single discharge is adequate for river restoration design. Proponents of single design flow methods (e.g., Rosgen and Silvey, 1996; Watson et al., 1999) have offered a practical means of designing river channels; however, the validity of dominant discharge based design has been challenged by many. For example, Williams (1978) and Nash (1994) showed that the recurrence interval of Q_{bf} varied widely for many rivers, and was not just simply $Q_{1.5}$. Variation in effective discharge measurements has recently raise the question of whether dominant discharge theory is valid for design purposes (Crowder and Knapp, 2005). Dominant discharge is a good tool for beginning the design phase of river restoration; however, a more comprehensive approach would be to model the full range of flows that might be encountered at a project site to explore habitat and stability. The additional time for and cost of investigating a full range of flows relative to current popular practices is a worthy investment given the central role discharge plays in shaping the aquatic ecosystem.

2.3.3 Channel Classification

A sub-set of measured geomorphic variables is frequently used to classify a river. There are many river channel classification schemes (see review by Niezgoda and Johnson, 2005). One of the earliest channel classification schemes was based on the watershed position of a river channel in the drainage network where headwater streams are called 1st order and the order increases when two like order streams converge (Strahler, 1952). Schumm (1977) also used watershed position to label streams by their role in sediment transport where headwaters are sources of material via erosion, mid-order streams mostly transport sediment, and large rivers are depositional zones (Figure 2.5).

Rivers are also fundamentally classified as alluvial or non-alluvial, which is indicative of the primary channel formation process and shape. Alluvial channels are self-formed in sediments deposited by the river under its present hydrologic regime. An alluvial river is capable of readjusting to its sediment load and thus the channels width, depth, and slope are directly related to the river's modern flow rate and sediment load.

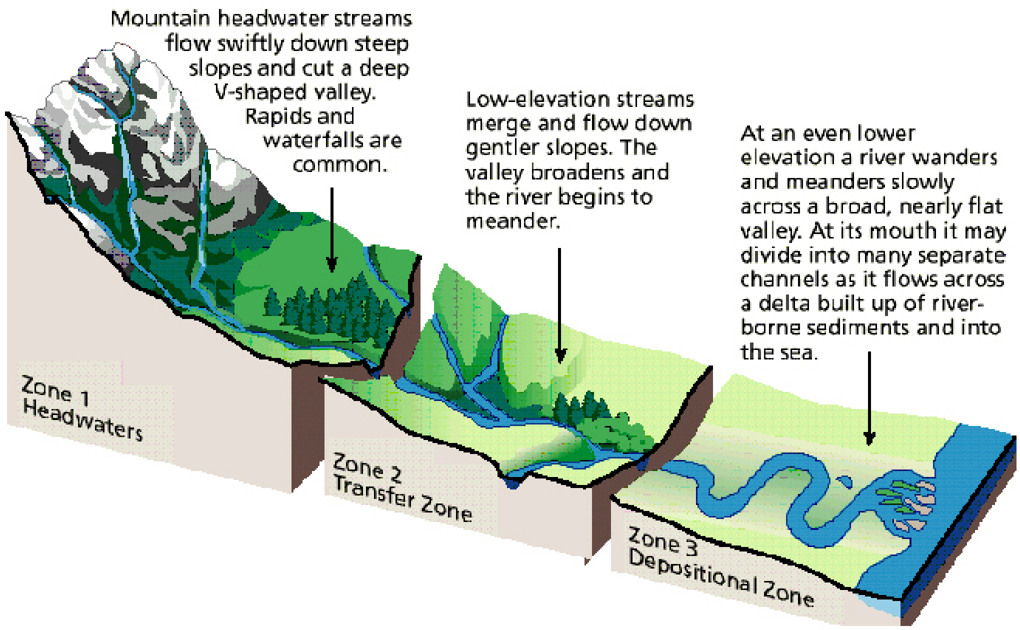


Figure 2.5: Longitudinal zones of a river corridor (Source: Schumm, 1977; FISRWG, 1998).

Alluvial rivers are typically characterized by larger meandering channels with significant areas of deposition that are situated in broad, low-gradient valleys. Non-alluvial channels tend to be relatively small, straight, and steep, and mostly export sediment from source areas in confined valleys in the upper watershed (Brierley and Fryirs, 2005). A threshold channel has stable bed substrate under normal flow conditions that acts like a fixed boundary with little bed material transport; however, bed material transport is initiated during high flood flows at a threshold velocity above which the channel has an active bed. Threshold channels can be found in both alluvial and non-alluvial rivers.

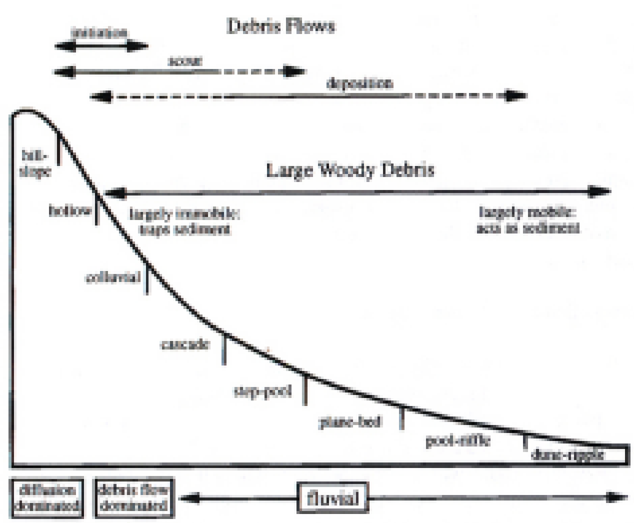
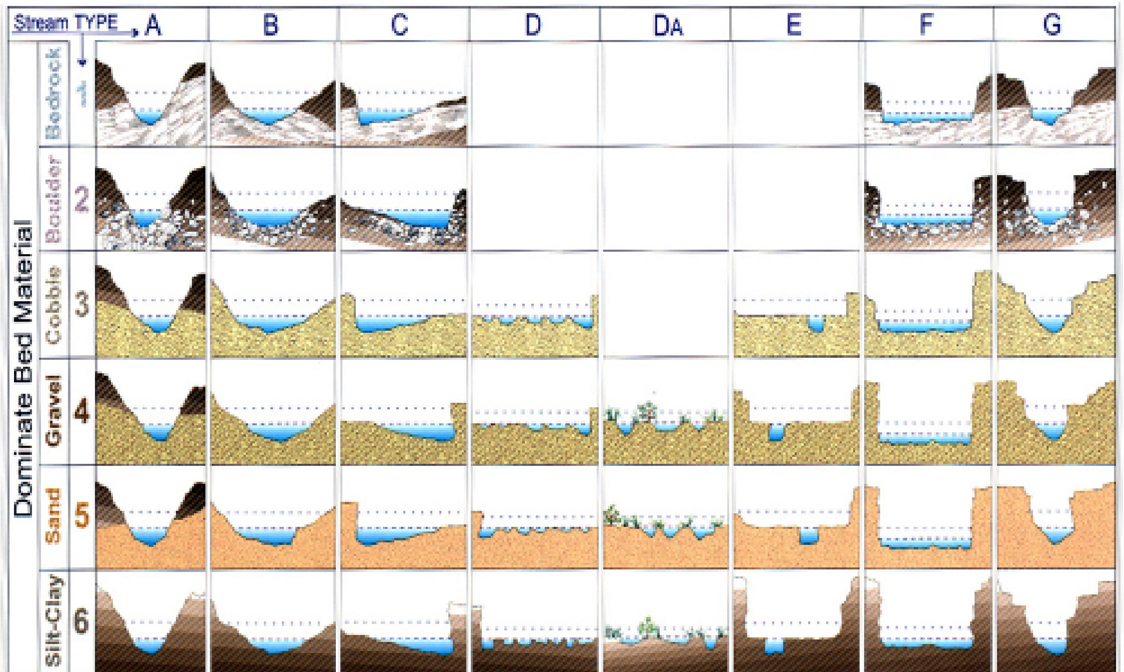


Figure 2.6: Montgomery and Buffington channel classification system primarily based on longitudinal watershed position (Source: Montgomery and Buffington, 1997).

Rivers can also be classified based on channel planform pattern (Leopold and Wolman, 1957). Montgomery and Buffington (1993; 1997) classified river channels based on both channel process (hillslope and valley evolution type) and form (profile form versus slope) (Figure 2.6). More recently, Dave Rosgen and Lee Silvey (1996) popularized channel classification and the fluvial geomorphology approach to river restoration via their system based on entrenchment ratio, width to depth ratio, channel sinuosity, longitudinal channel slope, and dominant substrate size (Figure 2.7). The principals of fluvial geomorphology and channel classification are valuable to the planning and design of river restoration projects as they are important complements to other integral design methods such as engineering modeling and empirical hydraulic geometry relationships.



	A	B	C	D	DA	E	F	G
Entrchmnt.	< 1.4	1.4 - 2.2	> 2.2	n/a	> 4.0	> 2.2	< 1.4	< 1.4
W/D Ratio	< 12	> 12	> 12	> 40	< 40	< 12	> 12	< 12
Sinuosity	1 - 1.2	> 1.2	> 1.2	n/a	variable	> 1.5	> 1.2	> 1.2
Slope	.04-.099	.02-.039	< .02	< .04	<.005	< .02	< .02	.02-.039

Figure 2.7: Rosgen channel classification system based on slope, sinuosity, width to depth ratio, entrenchment ratio, and dominant bed material (Source: Rosgen, 1994; Source: Rosgen and Silvey, 1996).

2.3.4 Channel Evolution

A critical piece of information to river management is the current and predicted future stage of channel evolution. This information helps answer questions related to the future stability of a channel, while considering the natural sequence of reach formation and impacts due to human disturbance (Brierley and Fryirs, 2005). For example, based on the stage of evolution it may be possible to know if a channel is expected to rapidly cut down (i.e., degrade or incise), build up (i.e., aggrade), or remain vertically stable. Channel

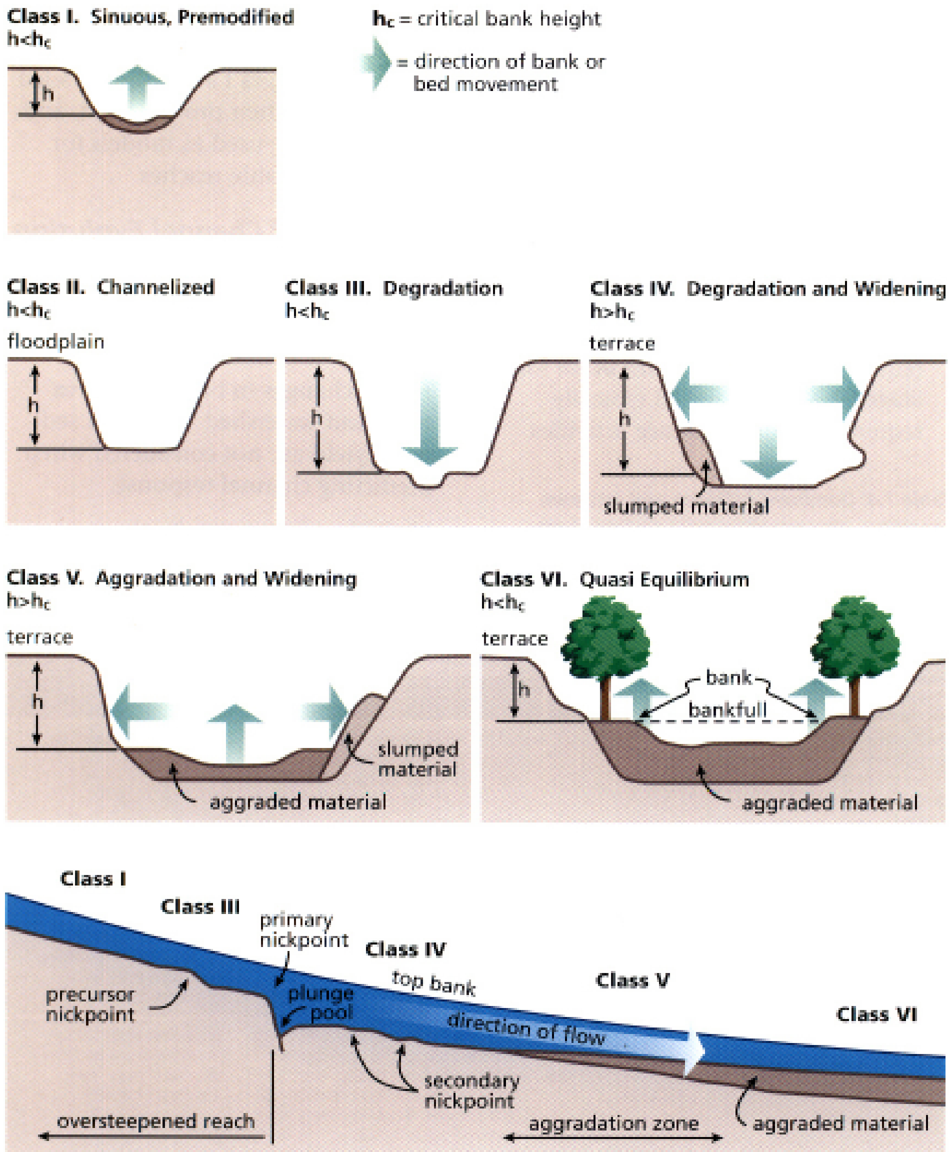


Figure 2.8: A schematic of the Simon incised channel evolution model (Source: Simon, 1989; FISRWG, 1998).

evolution also assists in understanding anticipated lateral adjustment processes such as bank erosion and/or deposition for floodplain creation. Schumm et al.(1984) created a channel evolution model to view the various stages a river goes through as it evolves in the landscape from stable channel, to degrading and eroding, to re-establishment of a new equilibrium at a lower elevation. This model has been adjusted for incised channels to offer a model of the evolutionary track in the commonly encountered degraded river (Simon, 1989) (Figure 2.8). Channel evolution stage is a critical piece of information when planning and designing a river restoration project and can help identify the sensitivity to system changes in the project area to increase the odds of a successful project. Evolution adds a long-term scale to the temporal aspects of river restoration design.

2.4 Integration of Physical, Chemical and Biological Processes

There has been a recent trend in the river restoration literature towards integrating the physical aspects of river systems (i.e., fluvial geomorphology, hydrology, and hydraulics) and biological assemblages; however, such work is still making its way into application. The union of these two components of the aquatic ecosystem is most apparent when investigating the quality of physical habitat available for organisms to carry out life cycle functions, and thus several means of qualitatively assessing habitat are widely used (e.g., Barbour et al., 1999; OhioEPA, 2001). More work is needed in this area to expand rapid assessment methods to incorporate a variety of river forms and the dynamic state of river processes. In addition to the link between physical and biological components of the aquatic ecosystem, water chemistry also plays an important role

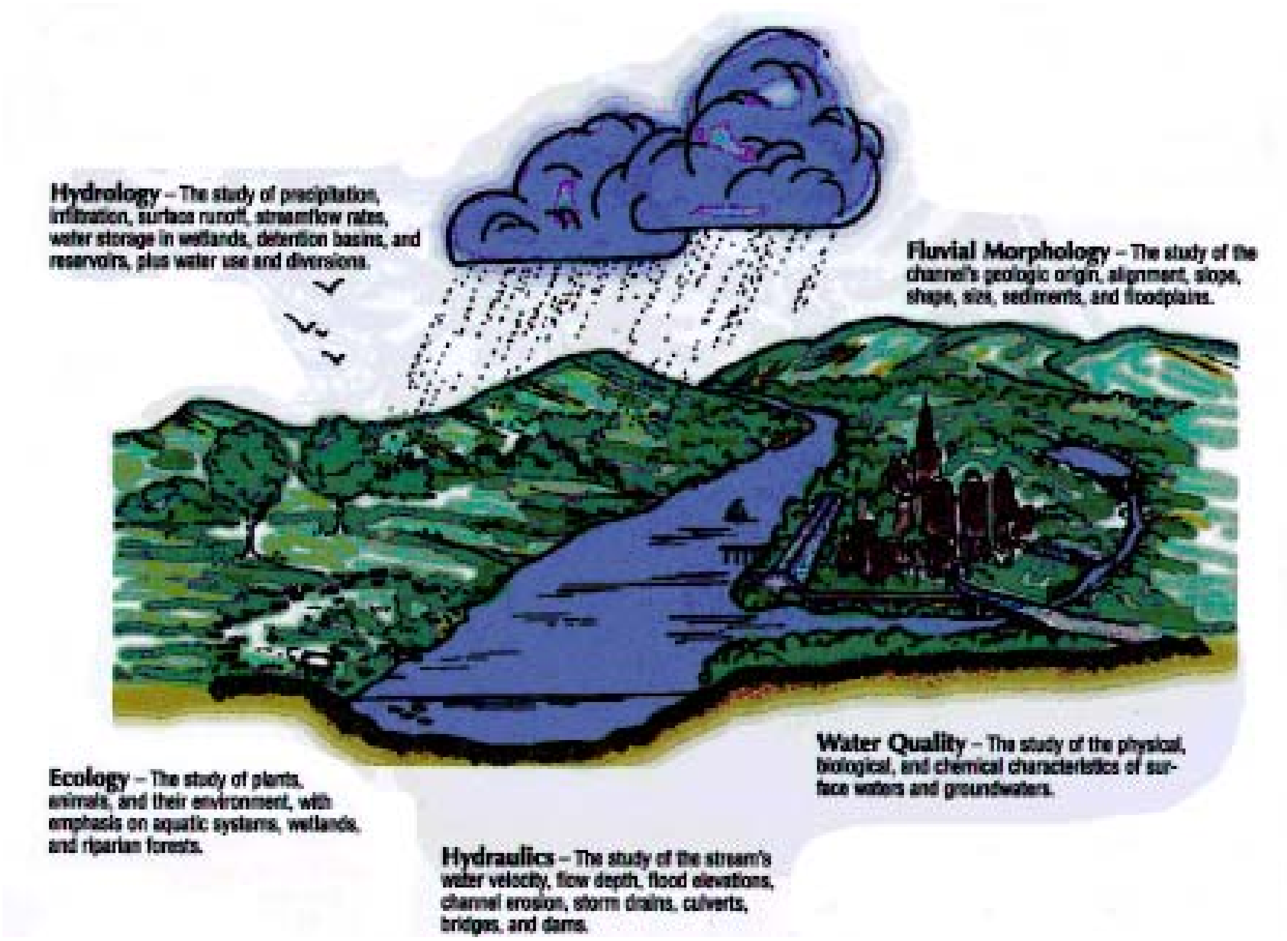


Figure 2.9: The multiple disciplines necessary for effective stream management (Source: MacBroom, 1998).

in determining the quality of existing habitat (Figure 2.9). Both the ionic background signals that are a function of the weathering of rock throughout a watershed and the superimposed chemical signal of runoff events together determine the physiochemical nature of a river. Parameters such as water temperature, pH, conductivity, dissolved oxygen, and turbidity are important water quality and habitat factors. Finally, the human dimensions of river management and restoration have emerged as a critical component of river restoration. Long-term stewardship and project success are often a function of the involvement of watershed partners during the monitoring, planning, design, and implementation phases of a project.

2.5 Conclusion

The short review of the central principals of fluvial geomorphology and related concepts presented here are important for understanding deviations from natural form and process and for river restoration. For more detailed information, the reader is referred to the library of key literature assembled during this review (Appendix A) and the annotated bibliography on river restoration manuals (Appendix B). The knowledge of the physical nature of a river is useful for planning and designing restoration, and is best used in conjunction with other existing tools such as engineering modeling and empirical-based design. The growing field of fluvial geomorphology has mobilized and popularized the river restoration movement, and will continue to play an important role in the restoration of rivers as methodologies advance.

3.0 THREATS TO NATURAL RIVER FORM AND PROCESS

> *"Against this backdrop of demographic, consumptive, and climatic pressures, rivers and the panoply of life they sustain would seem doomed. However, disastrous loss of freshwater biodiversity is not yet a foregone conclusion. Homo sapiens is among the life-forms that rivers sustain. At some point, the compulsion to save ourselves, as a species, will trigger an impulse to save the aquatic ecosystems that life depends upon." (Postal and Richter, 2003)*

3.1 Introduction

Native Americans and early European settlers used rivers for transportation, water, food, and waste export. As the population of the United States expanded, river water became more of a commodity for irrigation and small dams were built for using flowing water to generate mechanical power to operate mills. Railroad easements were placed in river corridors for the transportation of commodities and travel. As industrial activities were developed, water from rivers was used in manufacturing and processing applications. The rail network expanded and roadways were also placed in river corridors. The creation of hydroelectric power generation led to the emergence of tall dams along many large rivers. Today, we are left with a legacy of river use and abuse that has established controlling infrastructure, mismanagement cycles, and antiquated societal practices that collectively allow humans to live in very close proximity to small streams and large rivers often disrupting natural channel form and process. Beyond actions in the river corridor, changes to watershed land cover and increasing storm frequencies due to climate change add to the challenges of managing inherent conflicts within the river corridor. Until society makes a decision to live in harmony with natural river processes, water resource management will continue to be a costly, dangerous, and ultimately loosing endeavor.

3.2 Channel Alterations

At the root of the conflicts between human investments in the river corridor and natural river process is the alteration of the balance between water and sediment (Lane, 1955; OMNR, 2001). Increased flows of sediment starved water often found in historically degraded channels can result in continued incision, where the channel cuts down vertically and is disconnected from its floodplain. This essentially eliminates the primary mechanism of natural flood attenuation and leads to increased flow velocities and erosion in the river channel. On the other hand, increased sediment and reduced flows leads to aggradation causing the alteration of natural flow paths and possibly channel avulsion – rapid channel relocation. Both scenarios pose threats to human investments in the river corridor and illustrate a channel out of dynamic equilibrium (Figure 3.1). Human impacts to the river corridor frequently reduce or eliminate fish passage, degrade riparian

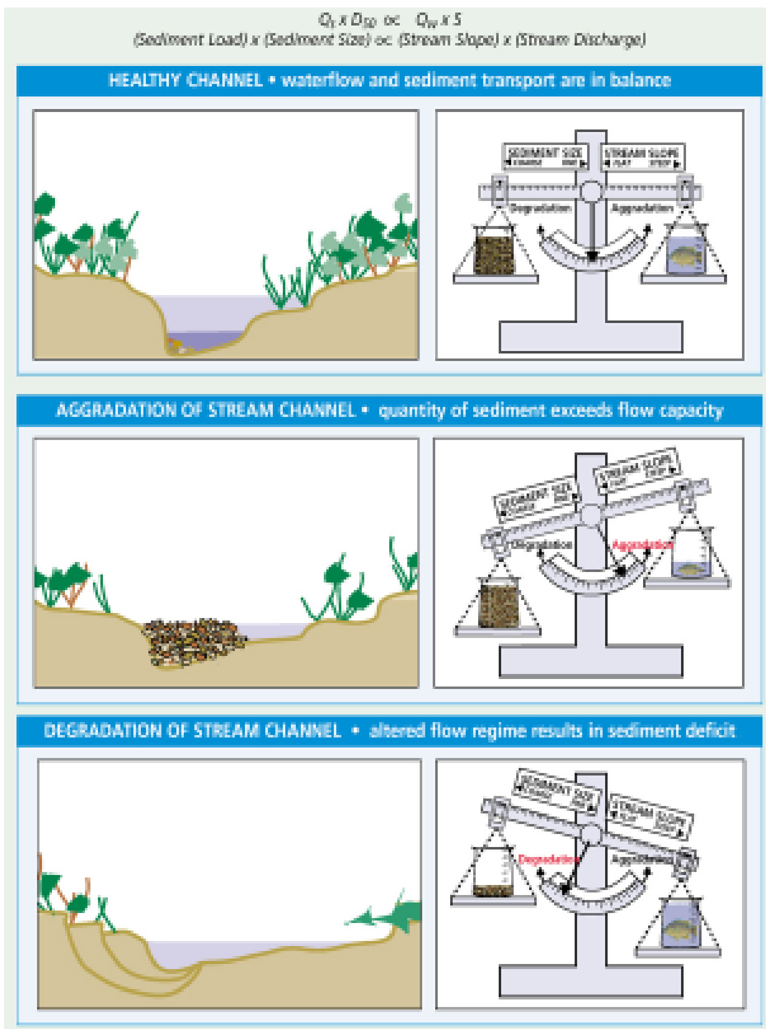


Figure 3.1: Schematics illustrating the disruption of the balance between water and sediment leading to aggradation or erosion (Source: Lane, 1955; OMNR, 2001).

habitat, and impair instream habitat. As they work to correct these problems and improve overall habitat, river restoration projects should always work towards achieving natural form and processes that will ultimately result in a self-sustaining system capable of producing necessary ecosystem services for both aquatic organisms and humans alike.

3.2.1 Straightening

Channel straightening has been used historically to facilitate the transportation of timber (Nilsson et al., 2005), to reduce flooding, and to allow for building infrastructure in the river corridor such as transportation easements. Straightening increases channel slope (channel rise / channel length) and decreases sinuosity (channel length / valley length) via a decrease in channel length by elimination of meanders. The resulting increased energy in the river channel can lead to accelerated deposition of eroded bank material for coarse-grained systems and to channel incision for fine-grained systems (Simon, 1992). Locations downstream of straightened reaches typically are more prone to flooding within the river corridor due to deposited sediments decreasing flow area. This scenario leads to costly, and often futile, management efforts to safeguard existing human investments. Channel straightening usually results in degraded instream habitat, where substrate and hydraulic diversity is homogenized and the channel's ability to retain organic matter is decreased. Historic channel straightening complicates natural process restoration given that the river channel wants to take on a different form within its valley.

3.2.2 Smoothing

Channel smoothing (Figure 3.2) is another method of managing flood risks in a given location in the river corridor that has negative impacts to instream habitat. Manning's equation $V = (1.49/N)(R)^{2/3}(S)^{1/2}$ indicates that water velocity increases as the roughness coefficient (N) is reduced by clearing vegetation and other types of roughness from a channel. Although it is common knowledge that instream roughness and riparian vegetation are important to channel stability (Wallerstein and Thorne, 2004) and biological integrity in the river corridor and channel (Cummins et al., 1989; Gregory et al., 1991), smoothing is still practiced today to

Figure 3.2: Channel smoothing via removal of bank vegetation in 2001 in the West River in New Haven County, CT (Source: R. Schiff).

limit flooding to developed areas located in historic floodplains. Although channel smoothing can reduce flooding locally, water is simply rapidly shunted downstream allowing the erosive force to alter channel morphology. If enough smoothing takes place, new flooding hazards can be inadvertently created. Smoothing is also done in the riparian areas adjacent to the river channel, which degrades floodplain and near-bank habitat.

3.2.3 Armoring and Canalization

Figure 3.3: Canalization and urban infrastructure such as buildings and utilities in the river corridor in the West River in New Haven County, CT (Source: R. Schiff).

Unnatural armoring, and the extreme case of canalization (Figure 3.3), is a common method for attempting to fix a river channel in place where infrastructure exists. Stone riprap, gabions, and cement walls are all traditional hard methods used to reduce lateral channel movement. Recall that in dynamic equilibrium, some lateral channel movement is expected. Although there has recently been a move towards using soft, deformable materials for bank stabilization, traditional methods are still most common today, often abruptly installed as a response to large flooding events (Eubanks and Meadows, 2002; Cramer et al., 2003). Like channel smoothing, bank armoring is usually a short-term solution to erosion problems, which ultimately alters channel morphology, changes sediment transport characteristics, and reduces the quality of instream and near-bank habitat (Fischenich, 2003). Canalization often reduces the number of pools, generates embedded substrates, and leads to an overall homogenization of instream habitat.

Bernoulli's equation for open channel flow ($E = V^2/2g + D$) indicates that the river's energy is a function of its velocity (V) and water depth (D). Erosion is one form of work that dissipates some of this energy; however, stopping this process in one location via bank armoring simply reflects and transfers the energy downstream to erode another location. The appropriate context for this management problem is to address the root causes of the increased energy (i.e., higher flow velocities and/or depths) in the river. Locations near streambanks are important instream habitat areas that are often degraded after application of bank armoring. In addition, the land adjacent to the river channel is altered by bank armoring that often results in reduction of critical habitat components such as overhanging vegetation, the lateral input of organic matter, and undercut banks.

3.2.4 Gravel Mining

Gravel mining and dredging significantly alter the sediment load moving through a river channel (Kondolf et al., 2001a). Historic and on-going sediment removal is responsible for changes to system hydrology, hydraulics, and morphology (James, 1999), and often results in the reduction of instream habitat quality due to an unstable streambed. Ironically, once an initial excavation takes place in an aggrading location, the need for continued maintenance is quite common leading to a costly management scenario that usually works against natural processes (VTDEC, 1999). Again, this is a challenging cycle to break out of. Such localized sediment adjustments must be viewed on larger scales, so that the balance between water and sediment throughout a watershed can be assessed and integrated in the goals of river restoration.

3.2.5 Dams

Dams have historically served many vital functions in society and continue to do so today. However, their mere existence alters the flow of water and sediment to the point that natural river form and process is an unrealistic objective of restoration unless dam removal is considered. Dams significantly reduce fish populations by blocking both migratory and resident species from historic spawning grounds.

Small dams alter flow, reduce sediment transport, increase downstream water temperatures due to solar heating in the upstream impoundment (Lessard and Hayes, 2003), and serve as physical barriers to fish migration. The collective impact of the many small dams scattered across virtually every river system is extensive. The removal of small dams is becoming a popular restoration option given that many of the structures are obsolete, safety hazards, and key sources of habitat impairment.

Large dams cause significant departures from a natural flow regime (Figure 3.4), often resulting in the general homogenization of flow patterns (Richter et al., 1996). For example, peaking hydroelectric operations create daily moderate flood pulses during generation that alter life cycle functions of aquatic organism.

Furthermore, large dams can reduce the magnitude of spring flushing flows important for sediment transport and habitat regeneration. Such unnatural flow regimes alter channel morphology and sediment regime (Assani and Petit, 2004), reduce the overall quality of river habitat making a river uninhabitable for some organisms, and eliminate many of the natural services provided by rivers (Postal and Richter, 2003). Large dams trap most of the sediment moving downstream, and significant erosion is common on tailwater reaches due to the release of sediment-starved water from the upstream impoundment (Kondolf and Swanson, 1993). The physiochemical nature of the water below a dam is largely a function of the location of the release, and can produce low dissolved oxygen levels for bottom releases and thermal heating for surface releases. Large dams block fish migration, and their individual influence on biological populations is typically more far-reaching than small dams. Fish passage alternatives for large dams have limited effectiveness relative to those for small dams. As a result, upstream access is not typically an option unless human intervention in the form of hauling fish upstream or stocking is used. Even if some reduced upstream population is maintained, large dams limit the ability for juvenile anadromous fish to move downstream and migrate out of the freshwater system to the ocean. The regular downstream movement (i.e., drift) of a substantial number of macroinvertebrates in a specific time period is an important means of habitat colonization (Allan, 1995) that is disrupted by large dams. During the river restoration planning phase, the benefits and disadvantages of existing dams, both large and small, should be weighed and incorporated into the system-wide view of natural form and processes, including the balance between flow and sediment.

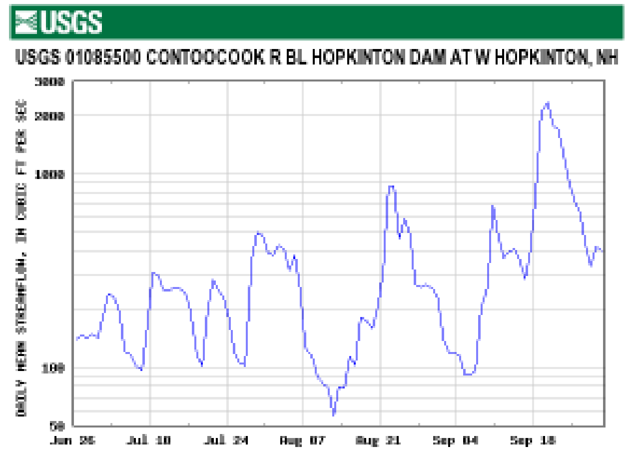


Figure 3.4: Hydrograph of altered flow regime associated with the Hopkinton Dam flood control/hydro-electric facility on the Contoocook River in Hopkinton, New Hampshire (Source: U.S. Geological Survey, Water Resources of New Hampshire and Vermont website, http://nh.water.usgs.gov/).

3.2.6 Diversions and Discharges

Water diversions and discharges are common in most streams and rivers. Low flows are the central issue regarding water diversions, and such activities have important ramifications to the geomorphic nature and biota of a river channel. A reduction of flow alters the balance between water and sediment, and can lead to aggradation in the channel. The combination of reduced flow and increased sediment on the streambed, particularly during warmer parts of the year, impairs habitat – limiting the ability for fish, benthic macroinvertebrates, and plants to live. Discharges to rivers are frequently a water quality issue as return flows from both point and non-point sources have different physiochemical characteristics than receiving waters. Nevertheless, discharges to streams also influence channel morphology by altering the water-sediment balance. All else being equal, increased flows mean more erosion and channels will tend to degrade. As with diversions, this often leads to localized habitat impairment.

3.2.7 Summary

Channel alterations disrupting natural river form and process are so widespread that it is difficult to find healthy reference reaches to serve as templates for restoration. The historic alteration of channels has left many channels incised and disconnected from their former floodplains. An incised channel is more unstable, has reduced spatial habitat heterogeneity, and often contains shifts in biological community structure (Shields et al., 1998). Limited flood dissipation areas increase the instream power during flooding because incised channels have limited mechanisms of energy reduction. The result is often continued channel incision. The incision-flooding-incision cycle is difficult to stop given the many human investments typically located in the river corridor, limiting options to reconnect a channel to its floodplain. Local, state, and federal managers are thus obligated to carry out costly activities and make substantial investments that are likely to fail because they oppose the river's tendency towards a natural state of equilibrium. Furthermore, these actions collectively impair aquatic habitat and biological populations. To emerge from this mismanagement cycle, all phases of river restoration must take into account the state of natural channel form and process that are allowed to take place throughout a watershed. This will not only help guide methods used for future project design, but also offer a more holistic view of where the project sits in relation to what is taking place in the watershed context.

3.3 Land Cover/Use Change

Channel impairment is also linked to land development in riparian areas and watersheds. Here, development refers to the conversion of naturally vegetated land cover for some human use. Land use change frequently takes place in close proximity to the channel as floodplains that have not been active for long periods of time are developed for agriculture and residential uses. The disconnect between historical floodplain condition, the cost to protect existing and new human investments in the river corridor, and recent river restoration goals is a key short-coming in many current permitting processes regarding activities in the river corridor. Land uses change also takes place away from river channels at higher elevations in watersheds.

3.3.1 River Corridor Development

The development in riparian areas, including floodplains, has contributed to the widespread destabilization and impairment of river channels. Additionally, this activity has set in motion a very costly management scenario where human investments are repeatedly protected from the forces of the river. It is in the river corridor that the conflict between natural form and process and human investments takes place.

The removal of vegetation in the river corridor increases flooding and exacerbates the impairments associated with channel alterations outlined above. Naturally vegetated buffers and extended floodplains reduce peak flows by delaying portions of incident storm runoff that must travel through hydraulically rough areas. The long, slow flow path also allows for sediment, nutrient, and pollutant removal. Furthermore, streambank stability generally increases with riparian vegetation due to hydrologic (i.e., interception and evapotranspiration) and mechanical (i.e., soil compression increases with root tensile strength) effects (Simon and Collison, 2002). The amount of erosion in the river channel increases with larger peak flood flows that result from the removal of natural vegetation. The result is often streambank erosion and channel degradation, and eventually the channel can no longer access its floodplain. At this point, all of the energy associated with runoff events is confined to the river channel and the threat to human investments dramatically increases. Riparian de-vegetation is a key contributing factor to altering river form and process and entering difficult management scenarios.

Existing infrastructure in the river corridor limits options and poses challenges to river restoration. Utilities, transportation networks, and structures create fixed (i.e., armored, canalized, or dredged) river management points that can be costly or politically unacceptable to change or re-locate. Such investments are important constraints to consider for project prioritization. For example, in some areas infrastructure deemed essential must be protected while artificially fixing a channel in place, while in other areas ample space can be provided for channel movement so that natural form and process can be established.

3.3.2 Forestry Operations

The change of land use in a watershed influences rivers via alteration of flow and sediment regimes, degradation of water quality, and impairment of local habitat. Tree removal during forestry operations reduces interception and evapotranspiration leading to an increase in storm runoff and peak flows (Lewis et al., 2001). Likewise, more sediment is typically mobilized due to forest road networks and heavy machinery, reduction of canopy cover, and stump removal (Mount, 1984). The changes to hydrology and morphology are most significant on streams near where logging occurs; however, for large operations, or many small ones in a given watershed, the changes to flow and sediment regime are evident in the down-gradient mainstem river. Water quality changes due to logging often include increased water temperature and turbidity. Mobilization of fine sediments smothers local habitat, limiting the biological potential for benthic organisms and complicating life cycle functions for all biota. Maintaining a harvest-free riparian buffer can help limit some of the river impairments associated with timber harvesting.

The northeast U.S. was heavily logged approximately 100 years ago when settlers moved to the region and cleared land for agriculture. With a subsequent decline in farming, many fields were abandoned and have undergone re-forestation over the past century, almost to the point that a similar amount of forest now exists in northern New England as before settlers arrived to the region (NERAG, 2001). The widespread existence of this re-forestation land cover pattern is evident by the presence of countless rock walls that wind through most of New England’s forests and once served as farm borders (Bell, 1985). This legacy land use pattern, with which more recent land use changes are superimposed upon, has contributed to the form and processes of modern-day rivers via watershed interactions. Current river management in seemingly undisturbed watersheds is thus taking place in areas that are actually undergoing widespread forest regeneration.

3.3.3 Agriculture

Agriculture leads to numerous impacts to rivers. The widespread smoothing of land for crop production, typically in floodplains, increases runoff and flood flows. River channel morphology and sediment storage in agricultural watersheds respond quickly to flood events due to the altered hydrology leading to increased threats in the river corridor (Knox, 1977). Given the frequent tilling and soil trampling, agricultural activities generate a lot of sediment that are transported to streams during runoff and erosion. Many streams near farms are also subject to water withdrawals for irrigation during the growing season. "The drainage networks of most tributaries are 'homogenized' in most intensively farmed regions" (Mount, 1984). Beyond the disruption of the channel morphology via altering the balance between water and sediment, reduced water quality is typical near farms where increased sediment, nutrient, pesticide, and salt concentration are common. Maintaining a naturally vegetated riparian buffer, livestock fencing to keep streambanks intact, rotational grazing, conservation tillage, and nutrient and waste management are a few of the tools available to improve aquatic habitat in agricultural areas. Such activities should be incorporated into river restoration planning.

3.3.4 Urbanization

"Dense human settlements, commercial and industrial centers, and transportation corridors in urban areas influence every attribute of stream ecosystems: the paths, timing, and volume of runoff that generates streamflow; the supply and size of sediment and organic material delivered to stream channels; the thermal and chemical characteristics of stream water; the structure, form, and materials of stream channels and aquatic habitats; and the demographics of the biological populations forming stream and riparian communities" (Konrad, 2003). Urbanization is the land use type that typically has the most negative impact on rivers due to the significantly altered flow and sediment regime. Impervious surface is at the root of the impacts associated with urbanization altering flow, sediment, water quality, and instream habitat. The urban drainage network, consisting of hard surfaces, gutters, drains, pipes, and countless local surface water discharges, short circuits the natural hydrologic cycle and rapidly moves water directly to urban channels (Figure 3.5). The increased flows typically increase rates of erosion leading to incised and over-wide urban streams (Trimble, 1997). Sections of urban rivers are often canalized, armored, or even enclosed in a conduit to protect the many human investments found in the river corridor, complicating the design of urban restoration projects (Niezgoda and Johnson, 2005).

Urban water quality is typically poor, and is often similar in character to that of sewage. Both industrial point sources of pollution and nonpoint sources (Figure 3.6) broadly distributed across an urban watershed degrade water quality. Impervious cover and limited natural vegetation leave riparian, near-bank, and local instream habitat poor. In a recent study investigating the appropriate scales of land use management, Schiff and Benoit (in review) show that instream habitat quality decreases with increasing impervious cover in the local riparian buffer. Water quality, on the other hand, is more closely linked to regional buffer land cover. Biological assemblages in urban rivers are more homogenous than those in natural settings. The management challenges in urban watersheds require adjusted river restoration practices given the fragmented nature of the river system and existing infrastructure. Gregory and Chin (2002) suggest addressing the condition, hazards, and restoration potential of each unique segment while maintaining an overall picture of the watershed, realizing that a variety of non-traditional classification and restoration approaches may be needed for urban systems.

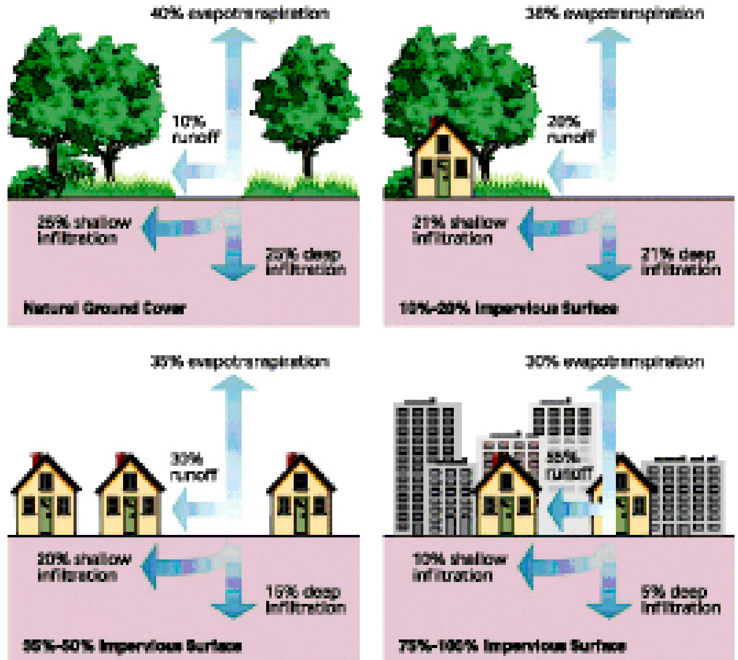


Figure 3.5: The effects of impervious cover on the hydrologic cycle (Source: FISRWG, 1998).

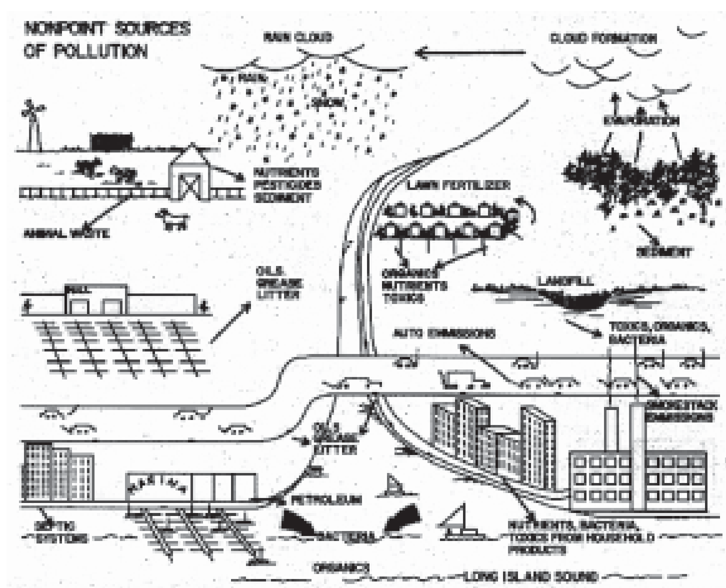


Figure 3.6: A schematic of the common origins of nonpoint source pollution (Source: Office of Long Island Sound).

3.3.5 Summary

Natural land cover, forestry operations, agriculture, and urbanization exemplify increasing departure from natural river form and process resulting in water quality and habitat impairment. Ultimately, biological diversity in river systems with developed watersheds declines as the intensity of development increases. This has been shown numerous times as a function of the density of logging roads, percent agricultural land use, and percent impervious cover. The planning and design of river restoration should take into consideration the prevailing watershed land use patterns to identify constraints and assist with project prioritization.

3.4 Climate Trends

Precipitation data from the National Climatic Data Center suggests an increase in the amount of precipitation in the northeast U.S. over the past 100 years (Figure 3.7). The Historic Climate Network database also shows a 3.7 % increase in precipitation in New England in the 1900's, with an apparent rise in frequency of more intense storm events (NERAG, 2001). The increase in precipitation over the past century is presumed to be linked to regional and global climate change, and would thus likely continue in the future. The regional precipitation increase could complicate the challenges associated with river corridor management and restoration programs. Higher flows generally coincide with wider channels, which will lead to additional conflicts in river corridors with increasing amounts of protected infrastructure. Furthermore, historical practices have left many river channels degraded and disconnected from their floodplains, and larger runoff events due to increased storm magnitudes would only increase the amount of energy confined within the channel. This scenario could result in expanded threats to human investments and aquatic habitat due to large erosion events (i.e., bank failures and channel avulsions) and

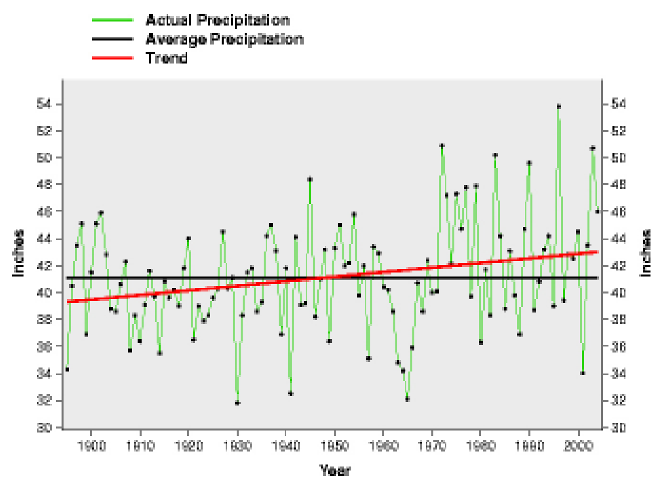


Figure 3.7: Precipitation records for the Northeast United States illustrating the increase in the amount of annual precipitation over the past century (Source: NOAA, National Climate Data Center, Climate at a Glance website, http://www.ncdc.noaa.gov/oa/climate/research/cag3/cag3.html, accessed 12/2005).

localized excessive deposition. Long-term restoration planning should incorporate some consideration of the potential for increased flows, and extended droughts, to properly assess possible future conditions in the river corridor.

3.5 Conclusion

The legacy of alteration of river channels and watersheds is quite extensive, and river restoration attempts to correct the resulting degraded habitat and return some level of natural channel form and process. Practitioners and managers must identify the appropriate spatial and temporal scales to provide a complete picture of the sources of impairment, the best possible solution, and how to implement and monitor the selected design. With this level of knowledge, only then will comprehensive management plans be generated that move future watershed, river corridor, and channel activities towards the over-arching goal of natural channel form and process that lead to channels that are stable, self-sustaining, and capable of supporting a diverse biota.

4.0 RIVER RESTORATION – CREATING CHANNELS AND STABILIZING STREAMBANKS

"Ecological restoration is a holistic approach not achieved through isolated manipulations of individual elements but through approaches ensuring that natural ecological processes occur." (Kauffman et al., 1997)

"Engineering solutions in urban streams have utility in some situations, but in most cases cannot fully mitigate the effects of development. Rehabilitation and enhancement of aquatic resources will almost certainly be required in all but the most pristine watersheds." (May et al., 1997)

4.1 Introduction

The challenge set forth by the Clean Water Act (1972) to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" is one which remains today, and is more frequently being addressed by river restoration. Millions of dollars are spent annually in the U.S. on river restoration (Moerke et al., 2004), and billions of dollars are expected to flow to tens of thousands of U.S. river restoration projects over the next few decades (Malakoff, 2004; Palmer et al., 2005). In addition, there has been a recent surge over the past decade in scientific research and publications on the topic (Shields et al., 2003a; Ormerod, 2004). Even with this significant commitment and growing public willingness to restore streams, there remain many fundamental needs in the field.

First, inconsistencies exist in describing projects, thus complicating application and resulting in a distortion of realistic project goals and actual biological potential. Second, a more comprehensive understanding of the spatial and temporal scales of the causes of impairment requiring restoration is needed to produce better designs and understand the potential mechanisms for improvement (Jansson et al., 2005). Third, practitioners must not rely on single design methodologies, but diversify and draw upon the variety of tools available for restoring streams to generate the most appropriate and effective projects. Fourth, consensus on general principals that constitute an ecologically successful river restoration project (e.g., Palmer et al., 2005) is needed to help standardize project implementation and evaluation. Fifth, more baseline and effectiveness monitoring is needed to understand if projects are actually leading to anticipated improvements, allowing for adaptive management of installations, and informing the science of restoration to improve methods (e.g., NRC, 1992; Bash and Ryan, 2002; ASCE, 2003; Moerke et al., 2004). Finally, continued efforts are needed to organize and refine the large amount of existing information on river restoration planning and design in a user-friendly format. It will take a unified effort on behalf of the river restoration community, including government officials, academics, and practitioners, to address these substantial needs and improve our means of restoring streams.

4.2 Restoration, Rehabilitation, and Enhancement

River **restoration** may be defined as the return of a resource to a healthy state where natural form, processes, and scales of disturbance and recovery are similar to conditions prior to human influence (NRC, 1992; Brookes and Shields, 1996; FISRWG, 1998). An on-going debate continues in the river restoration community as to the appropriate historical target for restoration, and if such an ambitious level of change is even possible (Booth et al., 2004). Based on this definition of restoration, it is evident that "it is a holistic process not achieved through the isolated manipulation of individual elements" (Shields et al., 2003a). The terms **rehabilitation** (sites initially impaired) and **enhancement** (sites initially average) imply a lesser goal of improving conditions relative to the existing watershed background. In developed landscapes where processes are altered due to widespread direct impacts to the river corridor and watershed land use change, efforts to improve river condition are more accurately called rehabilitation or enhancement.

4.3 Approaches to River Restoration

4.3.1 Active versus Passive

In certain instances a **passive** restoration program (i.e., no direct human intervention to change system form or function) is adequate to improve river condition once a source of impairment is removed. For example, installing livestock exclusionary fencing to allow for the natural re-vegetation of a trampled streambank can lead to improved bank stabilization and near-bank habitat, in addition to local natural channel form and process, without direct manipulation to the channel. Passive approaches can be appealing alternatives as they typically cost less than other methods and are effective means of moving towards system naturalization. Note that the "no action" alternative, nothing is done and the channel is left unchanged to move through its present evolutionary course, differs from the passive approach that includes indirect actions that lead to the cessation of a stressor. With the many threats to river systems found both in the river corridor and scattered throughout watersheds, cessation of disturbances is often not enough for system restoration given historical abuses and remaining infrastructure. In this case, **active** restoration is required to move river form and process towards a more stable and natural state. Recall that isolated rehabilitation and enhancement practices alone do not technically constitute restoration – a holistic process with multiple facets of assessment and project installation.

When its components are properly designed and implemented, the benefits of active restoration programs are typically apparent over relatively short time periods as compared to passive approaches. Proponents of active river restoration desire a more rapid feedback to quickly improve a degraded area and to fit work into existing typical project time tables. Although system recovery may not be as quick as with active methods, passive approaches are valued for their more natural assisted recovery. When establishing a restoration program, the pros and cons of both passive and active approaches should be considered for each project component. Although at times the division between passive and active practices may not be completely clear, both methods offer value to an overall restoration program and should be incorporated as needed to accomplish goals.

Components of active restoration can take place at any spatial scale, and are often carried out between the riffle to reach scales (i.e., meters to 1-2 kilometers). Common practices include installation of channel and bank features, re-shaping of channel and banks, daylighting, improving fish passage, and enhancing the riparian corridor. Occasionally, changes to infrastructure such as re-locating utility easements and retrofitting urban drainage networks to reduce their impacts are carried out as part of a river restoration plan. Schueler and Brown (2004) identify nine objectives of urban river repair: 1) cleanup river corridor; 2) naturalize river corridor; 3) protect threatened infrastructure; 4) prevent additional bank erosion; 5) expand or reconnect the river network; 6) increase fish passage and spawning potential; 7) improve fishery habitat; 8) achieve natural channel design; and 9) recover biological diversity and function.

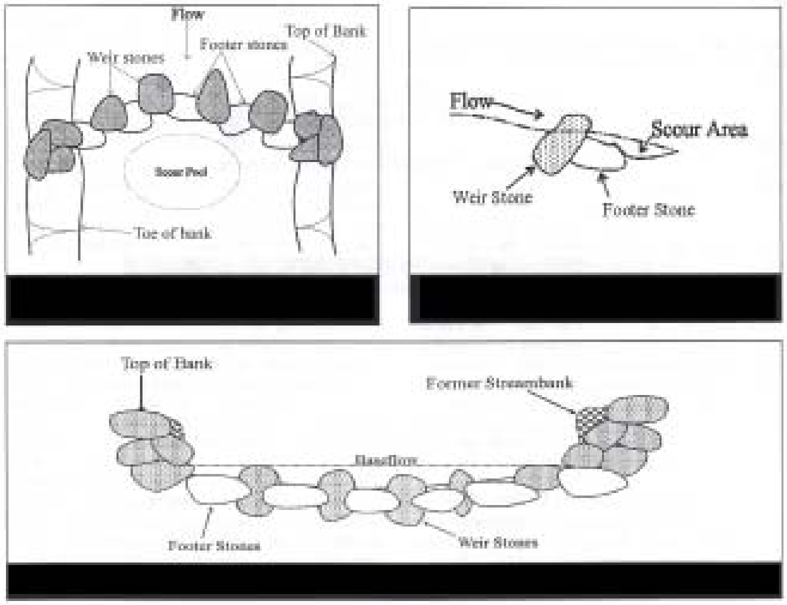


Figure 4.1: Sketches of plan, profile, and section views of a rock vortex weir (Source: Brown, 2000).

(A)

Coconut Fiber Roll

Cylindrical structures composed of coconut husk fibers bound together with twine woven from coconut material to protect slopes from erosion while trapping sediment which encourages plant growth within the fiber roll.

Applications and Effectiveness

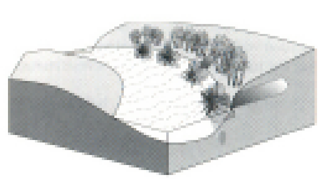
- Most commonly available in 12 inch diameter by 20 foot lengths.
- Typically staked near the toe of the streambank with dormant cuttings and rooted plants inserted into slits cut into the rolls.
- Appropriate where moderate toe stabilization is required in conjunction with restoration of the streambank and the sensitivity of the site allows for only minor disturbance.
- Provide an excellent medium for promoting plant growth at the water's edge.
- Not appropriate for sites with high velocity flows or large ice build up.
- Flexibility for molding to the existing curvature of the streambank.
- Requires little site disturbance.
- The rolls are buoyant and require secure anchoring.
- Can be expensive.
- An effective life of 6 to 10 years.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streamside vegetation.
- Enhances conditions for colonization of native vegetation.

For More Information

- Consult the following references: Nos. 65, 77.

(B)

Log, Rootwad, and Boulder Revetments



Boulders and logs with root masses attached placed in and on streambanks to provide streambank erosion, trap sediment, and improve habitat diversity.

Applications and Effectiveness

- Will tolerate high boundary shear stress if logs and rootwads are well anchored.
- Suited to streams where fish habitat deficiencies exist.
- Should, where appropriate, be used with soil bioengineering systems and vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation.
- Will enhance diversity in riparian areas when used with soil bioengineering systems.
- Will have limited life depending on climate and tree species used. Some species, such as cottonwood or willow, often sprout and accelerate colonization.
- Might need eventual replacement if colonization does not take place or soil bioengineering systems are not used.
- Use of native materials can sequester sediment and woody debris, restore streambanks in high velocity streams, and improve fish rearing and spawning habitat.
- Site must be accessible to heavy equipment.
- Materials might not be readily available at some locations.
- Can create local scour and erosion.
- Can be expensive.

For More Information

- Consult the following references: Nos. 11, 34, 77.

Figure 4.2: Sketch of (A) coconut coir fiber roll and (B) log, root wad, and boulder revetments used for streambank stabilization (Source: FISRWG, 1998).

Table 4.1: A summary of existing manuals and books that contain details of stream restoration practices.

Practice used for…	Details	Reference (see Bibliography)
Streambank stabilization	Bioengineering only	(Eubanks and Meadows, 2002) (Walter et al., 2005)
	Hard and soft methods	(NRCS, 1996) (Cramer et al., 2002)
Instream and streambank work	Hard and soft methods	(TRANS, 2001) (FISRWG, 1998) (Saldi-Caromile et al., 2004) (MDE, 2000) (Flosi et al., 2002) (Hunter, 1991) (Riley, 1998)

The specific practice to be installed is a function of its objective and the prevailing conditions. For example, a rock vortex weir (Figure 4.1) might be used where fixed grade control is called for. Instream boulders and debris jams are common components of fish habitat enhancement projects. Large-boulder, log, root wad, and coir fiber revetments (Figure 4.2) are practices commonly used for bank stabilization. Re-vegetation is frequently performed on streambanks and in riparian areas to reduce erosion potential and enhance near-bank habitat. Many existing river restoration manuals and books contain detailed catalogs of popular practices the include descriptions, application notes, and installation specifications (Table 4.1). These documents serve as useful guidelines to design features of river restoration programs.

4.3.2 Analytical

The analytical, or physical-based engineering, approach has played a key role in both the original and recent methods of river restoration. Hydraulic analysis was initially used to design open irrigation channels that were in regime, or transporting all incident sediment while maintaining stable dimensions. Since then, the fundamentals of hydraulics (e.g., Chezy, Manning's, and continuity equations) have been applied to virtually every aspect of open channel design, including recent efforts in creating naturalistic channels. Analytical modeling techniques are becoming a more prominent part of comprehensive river restoration design due to the benefits of estimating system hydrology, water surface elevations, and sediment transport rates (Burns, 1998). Millar and Quick (1993) incorporate bank stability as a function of consolidation of the bank sediment, cementing by fines, and binding of the sediment by root masses into an analytical hydraulic geometry model. Furthermore, analytical methods have been used to investigate the hydraulic characteristics of incised streams with regard to channel evolution stage (Bledsoe et al., 2002). There has been a recent trend of using analytical models to elucidate the connections between small and large-scale river processes (de Boer et al., 2005).

A central benefit of analytical modeling approaches is the ability to model designs with both spatial and temporal dynamics. At one point in time analysis methods were quite cumbersome and time-consuming, but these problems no longer exist due to advances in modern personal computing and the internet. A variety of useful programs are available through both public domain and private software distributors. As with all computer-assisted modeling, a drawback of using modern analytical tools is that errors can be hidden in the code of models that could skew designs. It is imperative that software users understand the fundamental technical theory underneath the buttons and menus of a modeling program to minimize errors. Analytical methods take time to set up and debug, and thus can increase project costs. Equations and numerical analytical tools can appear abstract to the public, and thus they are often not as readily digestible by project stakeholders as compared to more visual approaches to river restoration.

Fundamentally, the problem with analytically modeling natural river channels is that they can have up to nine degrees of freedom (variables) and there are insufficient physical equations to generate a solution (Hey and Thorne, 1986). Therefore, empirical or analog data is also needed. The independent variables are usually watershed area, dominant discharge, and sediment load. The dependent variables are channel width, depth, slope, sinuosity, substrate, and bank slope.

4.3.3 Empirical

The empirical approach to river restoration relies on extensive data sets to develop regression relationships to predict stable channel dimensions at new sites. Leopold and Maddock (1953) expanded this approach by identifying power functions for channel width, depth, and velocity as a function of discharge, based upon the Lacey regime equations (1930). Since their creation, hydraulic geometry relationships have been utilized in many ways to assist with river assessment and restoration. For example, relationships have been created that are a function of watershed drainage area (Montgomery and Gran, 2001), particular to a given region (e.g., Castro and Jackson, 2001), and a function of channel gradient that was found to drive the dimensions of confined mountain streams (Wohl et al., 2004).

An important benefit of empirical approaches includes the establishment of rapid design tools once relationships for a given region and river type are established. However, design errors can occur when relationships are used in systems that differ too substantially from the one in which they were established. Citing the differences in form and process between natural streams, where most hydraulic geometry relationships are created, and urban rivers, Niezgoda and Johnson (2005) indicate that there is a significant research need to extend the utility of empirical methods to altered systems. Other potential pitfalls include spurious observations skewing data patterns during relationship calibration and limited opportunity for understanding watershed processes.

4.3.4 Analog

The analog approach to river restoration uses a reference reach as a template for stable form and a single dominant design discharge. Dimensions are measured at the stable reference reach and replicated when constructing a new channel. The bankfull discharge is most commonly used for design, and is identified at the reference reach based on field indicators of its elevation, or at an existing gauge. The analog approach is closely associated with the Rosgen method (Rosgen, 1994; Rosgen and Silvey, 1996, 1998), and many existing river restoration design manuals and guidelines primarily follow this methodology for channel creation (e.g., TRANS, 2001; Flosi et al., 2002; KST, 2002; Doll et al., 2003). This geomorphic approach has become very popular over the past decade due to expanded opportunities for learning design methods and installing projects. The proponents of the analog approach cite such benefits as simplistic observation-based design relative to engineering approaches, increased opportunities for stable channels due to use of a local reference, and the relative efficiencies of the approach.

There is a recent increased movement in the river restoration community that the analog approach is not as straight forward as anticipated and should not be used alone for channel design. Inconsistencies can arise that are associated with identification of bankfull levels and classification of the dominant channel material (Simon et al., 2005). Reference reaches are often difficult to find in disturbed systems leading to guesswork in a fundamental component of the design approach. Reliance on a single flow is another troubling aspect of the analog method. For example, channels designed with sole reliance on a dominant discharge having a recurrence interval of 1-2 years are susceptible to degraded instream habitat quality during low flows, instability due to repeated moderate flood events, and even complete channel avulsion during extreme floods.

4.3.5 Combination

None of the above design approaches is universally applicable, and thus the need exists to understand each method and how to select the appropriate design tools for a given project. River restoration practitioners are just starting to break out of single approach methods to utilize the positive aspects from analytical, empirical, and analog methods to establish interdisciplinary, practical, and detailed designs. Soar and Thorne (2001) advocate 'the geomorphic engineering approach,' where the analog approach is combined with analytical tools to model a range of flows and sediment transport. Shields et al. (2003b) describe an intermediate approach featuring application of hydraulic engineering tools for assessment of watershed geomorphology, channel-forming discharge analysis, and hydraulic analysis of flow and sediment transport. The increased initial investment in design expands the likelihood that installed projects will meet project goals, and not be prone to failures such as dislocation during large flood events or reduced habitat quality during low flows. The comprehensive design approach is ultimately more economical as project failures require costly repair and maintenance. In addition, combined approaches allow for more flexibility to carry out process-based design approaches (Simon et al., 2005).

4.4 Project Understanding via Appropriate Classification of Created Channels

Natural channel design has moved river restoration from 'unnatural rigid design' closer to nature. In this form-based approach, natural-like features are re-created although natural processes are often not allowed to play out. The common usage of 'natural channel design' is more accurately called 'semi-natural form design' due to the use of artificial structures, while a fully natural channel creation is called 'natural process design'. This more accurate classification of created channels based on geomorphic characteristics helps elucidate the attainable habitat details of a project, important design principals, and the likely social components (Table 4.2). Many of these important aspects of channel design are commonly lumped into planning procedures under problem identification and project objectives; however, a clear classification scheme

Table 4.2: A created channel classification system based on fluvial morphology characteristics that can be used for accurately describing anticipated habitat condition, important hydrologic design tools, and significant social aspects of stream restoration projects.

		Unnatural Rigid Design	Semi-Natural Form Design	Natural Process Design
Fluvial Geomorphology	Form vs. process	N/A	Form	Form and process
	Planform	Constrained	Partially constrained	Unconstrained
	Profile	Uniform	Non-uniform	Non-uniform
	Cross-section	Uniform, prismatic	Non-uniform, variable	Non-uniform, variable
	Floodplain connectivity	Absent	Variable	Present
	Channel stability	Rigid	Threshold	Equilibrium
	Channel evolution	Static	Static	Dynamic
Habitat	Biological potential	Limited	Rehabilitation/enhancement	Restoration
	Eco-hydraulics	Homogenous	Variable	Heterogeneous
	Substrate	Homogenous	Variable	Heterogeneous
	Streambanks	Hard	Combination	Soft
	Near riparian	Unvegetated	Partly vegetated	Vegetated
	Connectivity	Limited	Typically limited	Lateral and longitudinal
Design	Flood magnitude	Large flood	Bankfull discharge	Low to high
	Sediment regime	Limited information	Limited information	Known
	Method	Empirical & analytical	Analog and analytical	All
	Type experience	Higher	Medium	Lower
	Primary goal	Flood conveyance	Improve structural form	Restore process and form
	Resiliency	High	Variable	Self-sustaining
	Long-term cost	Medium	Medium to high	Low to medium
Social	Aesthetics	Low	Medium to high	High
	Infrastructure	Present	Moderate	Minimal
	Community risk	Low to Medium	Medium to high	Low to medium to high
	Stakeholder involvement	Low	Medium to high	Medium to high
	Public access	Low	Variable	Variable
	Public experience	Moderate	Moderate	Low
	Funding	High	Medium	Low

based on project type is a valuable tool for guiding channel creation, streambank stabilization, and other types of river restoration.

4.4.1 Unnatural Rigid Design

Unnatural rigid channel design uses hard materials to fix channels in place in all dimensions, and eliminate natural processes and evolution. This river management method is often applied after large flood events to stabilize streambanks and bed. In addition, rigid channels are common in developed areas where human investments, and associated risks, are abundant in the river corridor. Although rigid design is effective at reducing local risks in the river corridor, under this design approach problems are mostly transferred to other locations. In addition, a general homogenization of habitat results from this method and severely limits biological potential. Virtually all aspects of the food web are disrupted and rigid channels typically have low biological diversity at all trophic levels.

Unnatural rigid design is based on handling large floods, and thus utilizes analytical and empirical methods to ascertain hydraulic capacity. Little, if any, information on the sediment transport capacity of the channel is used during design. Engineers have a lot of experience in rigid, open channel design, yet these installations frequently require periodic maintenance as materials are re-located during flooding. Many guidelines exist for identifying the appropriate material size for stabilization (e.g., NRCS, 1996; Fischenich, 2001) and for design principals (e.g., USACOE, 1994; Richardson et al., 2001).

Rigid channels are still used today as they are effective at reducing risk to local human infrastructure in the river corridor. Nevertheless, their lack of aesthetics, reduced access, and limited stakeholder involvement during planning and implementation is making other more naturalistic projects more popular to watershed partners. In addition, natural designs are more favorable as there is a growing desire for environmental restoration to strengthen the link between humans and the natural world (Light, 2000), and restore ecosystem services.

4.4.2 Semi-Natural Form Design

Semi-natural form design, commonly referred to as natural channel design, is based on replicating an analogous channel reach where stable form is present. This form-based method has popularized the analog approach to river restoration, where fluvial morphology is the primary means of assessment and project design. Again, the new naming convention of semi-natural form design is presented because somewhere during the natural channel design panacea of the past decade information regarding truly natural channel restoration seems to have been largely ignored. For example, semi-natural form design typically has a partially constrained planform to limit channel migration, and thus channel evolution is halted. It is this control that both limits restoration potential, but allows for a more natural design approach where site constraints and human investments are present in the river corridor. The increased hydraulic and substrate heterogeneity in semi-natural form design over rigid channel methods improves habitat and increase the biological potential of created channels. Partially deformable streambanks and maintenance of some riparian vegetation add to the natural-like features and increase the feasibility of accomplishing the goals of system rehabilitation and enhancement.

Semi-natural form design is usually based on using the bankfull discharge as the dominant channel forming flow. As with unnatural rigid channel design, this design strategy of using a single flow to shape a channel can be problematic (Simon et al., 2005) rather than investigating the range of typical flows. Nevertheless, semi-natural form design is currently one of the most popular means of river restoration (e.g., Rosgen and Silvey, 1996). Public demand for increased aesthetics and access, improved habitat in constrained project areas, and continued involvement in the restoration process have promoted this design method. Mixed success rates in meeting project goals illustrate that popular design methods must continue to be refined (e.g., Kondolf et al., 2001b). Nonetheless, semi-natural channel design remains a popular mechanism of ecosystem rehabilitation and enhancement, naturalization, and community revitalization in developed areas.

4.4.3 Natural Process Design

Natural process design restores channel form and processes where all dimensions remain unconstrained and channel evolution may take place. This truly natural channel design method leads to a heterogeneous and deformable channel in dynamic equilibrium. Natural process design is only possible where constraints are limited so that longitudinal barriers are absent and lateral connectivity to the floodplain is a realistic objective. Connectivity is an important aspect of river restoration that is often overlooked (Smith et al., 1999). Natural channel form and processes allows for the establishment of high quality habitat for all flow conditions and biotic life-stages leading to the potential for full biological restoration.

Natural process channel design is comprehensive, covering a range of flows and sediment regimes, but is simplified due to the absence of physical project constraints. Empirical, analog, and analytical methods are required to fully understand how to attain natural process and form. If properly designed, natural process design should require little to no maintenance, create minimal risks to humans, and will likely generate valuable flood attenuation and sediment retention to improve conditions at downstream locations.

Natural process design has received little attention due to limited willingness to invest in projects to improve natural processes in less-developed areas. This has resulted in limited experience and funding for natural process design. As the importance of natural form and processes becomes widely known by watershed partners, natural process design will likely become a more popular component of river restoration.

4.5 Over-Arching Goals of River Restoration

The specific goals of river restoration will vary based on the nature of the system disturbance and the practices used to intervene. Recall that often times full restoration is not possible and projects will seek to rehabilitate or enhance a component of a system that has disrupted processes. Even with the variety of objectives, researchers and practitioners have started working on standardizing common goals of restoration to attain consensus and move the science and application of river restoration forward. Most recently, a group of leading aquatic scientists (Palmer et al., 2005) discussed five criteria for an ecologically successful restoration project.

1. A guiding image exists: a dynamic ecologic endpoint is identified a priori and used to guide the restoration (within present regional context).
2. Ecosystems are improved: the ecological conditions of the river are measurably enhanced and move towards the guiding image.
3. Resiliency is increased: the river ecosystem is more self-sustaining than before.
4. No lasting harm is done: implementing the restoration does not inflict irreparable harm.
5. Ecological assessment is completed: some level of pre- and post- project assessment is conducted and the information is shared.

These criteria for success appear to be broad enough to include a range of project types (i.e., from unnatural rigid design to natural process design) in systems with variable conditions. The first three criteria are inherently about process – (1) identification of system processes, (2) observable process improvement, and (3) resiliency that is maximized under natural processes. Reference to a 'guiding image' implies that targets are not always healthy reference streams, but expectations must be adjusted based on existing system constraints. Criterion four addresses a common problem in many current restoration programs in that installed practices are addressing one aspect of recovery while simultaneously limiting another aspect. Process-based thinking helps reduce such restoration conflicts. Finally, the fifth criterion addresses the current severe lack of river restoration monitoring, calling for expanded evaluation and reporting to observe changes and advance the science of river restoration. The criteria mentioned above are representative of those found in other river restoration manuals.

Reoccurring themes regarding project goals are scattered throughout existing river restoration manuals (e.g., KST, 2002; Saldi-Caromile et al., 2004) and collectively call for a clear definition of the desired future condition, identification of important spatial and temporal scales, recognition of constraints and key issues, and clearly defining goals and objectives at the project start. "This vision will ultimately be integrated with important social, political, economic, and cultural values" (FISRWG, 1998).

4.6 The River Restoration Process

4.6.1 Introduction

Several existing manuals and documents offer useful methodologies for the river restoration process (Miller et al., 2001; OMNR, 2001). Some standardization of project planning appears to be taking place; however, widely applicable design methods are not available and at times cautioned against. Common themes encountered for use in the river restoration process follow.

4.6.2 Monitoring

If at all possible, river restoration should be conducted in the context of an on-going monitoring program to inform the process from the problem identification state all the way through to effectiveness monitoring (Ralph and Poole, 2003). For example, channel and streambank assessments (e.g., engineering slope stability analysis or bank erosion hazard index assignment) can assist with problem identification and informing the design process. The necessary amount of data for effectiveness monitoring is often not present. In many cases, the lack of baseline monitoring precludes pre-post comparative studies so post-treatment only study designs and analytical tools can be used to investigate effectiveness after project implementation (Schiff, 2005). In the end and with ample foresight, as much preliminary monitoring that can be budgeted for should be performed at the project site, reach, segment, and watershed. This monitoring should span the disciplines of geomorphology, hydrology, hydraulics, physical habitat, aquatic biology, and water chemistry. During the early phases of project planning, all pertinent existing data potentially related to the project (e.g., maps, photos, previous projects in the watershed, previous assessments, etc…) should be assembled.

4.6.3 Problem Identification

A critical component of project planning is proper problem identification. This includes the appropriate spatial and temporal scales at which disturbances are operating. For example, it is critical to the early design phases of the project to know if the problem is localized or originating at the watershed scale, and if the disturbance occurs regularly at some recurrence interval. A key to truly process-based restoration is to understand the mechanism that are causing the disturbance (Jansson et al., 2005), so that these functions can be directly addressed during the project design phase. During the preliminary monitoring and problem identification phase, it is useful to gain an understanding of the range of variability of natural form and process, as well as levels of disruption. A clear identification of the problem will lead to a more accurate formulation of goals and objectives, design, and implementation. Accurate problem identification and understanding of causal mechanisms will also help determine if 'no action' or passive restoration alternatives are possible, which may be preferable to active restoration implementation.

4.6.4 Goals and Objectives

After preliminary monitoring and problem identification and understanding, a guiding image must be conceptualized for what the river should look like and how it should function once the project is complete. This image is not limited to the project site, but should extend to the reach and watershed spatial scales. Additionally, the guiding image should project into the future when more components of some over-arching restoration program might be completed. For example, characteristics associated with the connection between a healthy river and an undisturbed wetland complex might be identified as a guiding image for a project site where floodplain connectivity is being restored for flood attenuation. However, it will require some forecasting to develop a guiding image of a watershed with enough floodplain reconnection projects to reduce flood flows in the channel to influence sediment transport and system wide channel form.

Project planning is a crucial aspect of the river restoration project because "well-intentioned projects often drift from having initially sound restoration objectives to ultimately providing reduced ecological benefit"

(Gillilan et al., 2005). In some cases, problems are not properly identified, goals and objectives are not clear, constraints go unidentified, and the level of risk acceptable by project participants often decrease as projects progress closer towards implementation. To help avoid 'guiding image drift' that often leads to inaccurate expectations in terms of recovery of the multiple facets of river ecosystems, we have created the classification of created channels to set realistic goals and objectives. As described above, the classification is based on morphological characteristics of channels created by unnatural rigid design, semi-natural form design, and natural process design. Selection of one of these project types will assist with understanding habitat and biological potential, useful design components, and anticipated social aspect.

Project participants and watershed partners play an important role in the river restoration process and will hopefully become a mobilized stakeholder group for future water resource protection and management. The community is essential to helping set appropriate goals and objectives for projects and river restoration programs, and should be involved as these are being formulated. Local watershed partners often bring to the table knowledge of politically popular ideas, a long-term database of historical information, and an understanding of the investments associated with on-going maintenance that are all important to accurate problem identification and formulation of goals.

4.6.5 Alternatives and Selection

After review of existing data and preliminary data collections on existing conditions, a qualitative discussion of alternatives is compiled for presentation to the project community. During this phase, the design team presents all potential alternatives in terms of how each does or does not meet the project goals with the given constraints. This process often rapidly eliminates several alternatives. Throughout this process it is important to maintain reference to system restoration, in addition to local rehabilitation and enhancement efforts. In the end, several alternatives should be selected via consensus to begin analysis. The details of the alternatives analysis vary by project; however, iterations of removing alternatives are possible until the project community is left with several that will be analyzed for potential selection as the final design.

4.6.6 Design

Alternatives that meet project goals, work with given constraints, and are selected by the project community for further investigation are then analyzed. Ideally, a combination of the analytical, empirical, and analog approaches is used to generate and check design options. For example, channel dimension for channel construction can be initially set by existing hydraulic geometry formulae (empirical) and verified by geomorphic assessment and comparison to a reference reach (analog). Furthermore, hydraulic and sediment modeling can be used to adjust channel dimension to ensure desired conditions exist over a range of flows (analytical). Adequate design, using each of the river restoration tools, and communication of findings will assist the project community select a final design for implementation. Final design selection is often an iterative process.

4.6.7 Implementation

The most organized, inclusive, and effective planning and design process is futile without proper implementation of river restoration components. If contractors are needed to complete the project, those with experience working in streams and a proven track record of high quality work should be selected. All field volunteers should be adequately trained on installation techniques. A member of the design team should be present to monitor as much of the construction as possible. This will increase the accuracy and efficiency of the implementation process. Throughout the construction phase, an effort should be made to minimize harm done to the system so that post-construction recovery can take place rapidly. Finally, post-construction plans should be generated to document activities in the river and serve as baseline data.

4.6.8 Monitoring and Adaptive Management

Just as it started, the project should end with monitoring and reporting of results. Ideally, a previously established monitoring protocol can be maintained with an on-going river restoration program; however, post-project collection can be used for effectiveness monitoring as well. Monitoring addresses important questions that otherwise go unanswered. Effectiveness monitoring ultimately determines if the project is meeting the goals of the installation and the overall restoration program. Monitoring also will identify if adaptive management (Holling, 1978; OMNR, 2001) is needed in the form of maintenance or project expansion. Monitoring results should be communicated at the local, regional, and national levels as each river restoration project offers learning opportunities that should be capitalized upon. Watershed partners, both involved in the project planning and not, are likely to be interested in how local resources are being managed. Presentations to watershed residents are important to establish stewards of existing projects, monitoring teams, and political acceptance for future river restoration activities. Project information is also valuable to other regional water resource managers who might be involved in similar programs. Presentation of project details and findings at regional conferences will help the broader management effort. Finally, publication in industry, government, and peer-reviewed journals will help advance the science and practice of river restoration. Broad reporting on river restoration will also continue to unify members of government, academics, practitioners, non-profit affiliates, and the public to address the challenges of river restoration and ultimately improve current management efforts.

4.7 Moving Towards Standard Design Methods

The consensus on the standardization of actual design methods is that a one-size-fits-all approach is not possible. Clearly, differences in site conditions, range of practice applications, climate, geography, and other aspects lead to such a broad range of design sequences that standardization is complicated. Standardization of detailed design aspects is not feasible, yet some widely applicable tools can be created that help guide the design phase of river restoration projects.

The standardization of river restoration design begins with the fundamentals of channel form and process, and deviation in altered systems. Framed in the context of the balance between water and sediment and across the range of spatial and temporal scales, the problems that are corrected by river restoration can be organized. A key first step is thus accurate mechanistic problem identification. A critical next step to design standardization is to accurately assess the possible effects of a single project, and understanding this project's role amongst a larger restoration program that might include many individual projects. Embedded in this step of standardization is the setting of realistic goals and objectives. As alternatives are created, constraints and potential must be understood and thus utilization of the constructed channel classification system presented above is of value. An organized, broadly applicable, form and process based planning phase to river restoration is the first essential step to allowing for design standardization. Reduced planning efforts make for less-informed entrance into design phases and complicate the possibility of some standardization.

Existing conditions, goals, and project scope often guide the level of design needed. For example, a semi-natural form design will typically require more comprehensive analysis than natural process design due to the presence of site constraints. A single, small habitat enhancement project will clearly require less design than larger scale projects such as channel construction. For this type of small scale project analytical modeling of flow and sediment transport is beyond the project scope. Analytical methods will be very useful in systems where substantial problems are being caused by an altered balance between flow and sediment. The combination of approaches to river restoration is advocated, yet only a subset may be needed based on the type of project.

Aspects of the current theory, approaches, and details of today's applied river restoration techniques are largely published in a variety of existing manuals (e.g., NRCS, 1996; Watson et al., 1999; Copeland et al., 2001; Cramer et al., 2003). Each manual has its own area of strength, and can be drawn upon for application. For this information to be useful, a framework is needed to guide the river restoration designer through the project planning phase and into the design (as presented above), and to the existing information in the appropriate manual. Flow charts can be created to guide the designer towards a group of solutions, design approaches, and other useful information.

4.8 Conclusion

It is a critical time for the field of river restoration, where application methods are being revisited to understand why projects are often not meeting anticipated goals and how to improve design and application methods. More and more information is being reported on the restoration of streams and its popularity as a management tool is growing, as indicated by increasing expenditures. The literature advocates returning to the fundamentals of channel form and process to understand mechanisms of system alteration and set realistic goals and objectives given constraints. This information is essential to effective design. A constructed channel classification system is presented to clearly identify project type and to guide informed project planning. Only with this knowledge can the complicated design process be advanced towards a standardized set of actions drawing on the existing publications on applied river restoration. Several themes continuously re-emerge in the river restoration documents reviewed here and are summarized below in some axioms. (See the preface of Cramer et al., 2003 for useful expanded guiding principals of stream restoration.)

4.8.1 Fundamental Axioms for River Restoration

- Monitor – Baseline, effectiveness, as much as possible. Monitoring should be the first and last item in the planning process to ensure accurate problem identification, identifying change, learning from projects, and advancing the science of river restoration.
- Investigate the causes of impairment, restoration alternatives, and mechanisms for change at the appropriate spatial and temporal scales.
- Natural channel stability is not equal to channel immobility. "A stable channel is one that has neither a net deposition nor net erosion of channel substrate in the long term." (TRANS, 2001)
- "Work with, not against, a stream's natural form and function." (KST, 2002)
- Accurately classify project type based on morphology to understand habitat potential, design methods, and social aspects.
- Where unconstrained, the natural process design approach is less costly to design and implement, and more effectively balances fluvial geomorphology, hydrology, and habitat quality.

5.0 RIVER RESTORATION IN NEW HAMPSHIRE

"Geographies sometimes speak of the State [of New Hampshire] as the 'Mother of Rivers.' Five of the great streams of New England originate in its granite hills. The Connecticut River rises in the northern part, and for nearly one hundred miles of its winding course hems the shores of the state with a 'broad seam of silver.' The Pemigewasset River starts in the Profile Lake in the Franconia Mountains and joins the Winnipesaukee at Franklin to form the Merrimack, which at one time turned more spindles than any other river in the world. The Cocheco and Salmon Falls Rivers join at Dover to form the Piscataqua. In addition, two of the principal rivers of Maine, the Androscoggin and the Saco, have their beginnings in northern New Hampshire." (NH, 2005)

5.1 Introduction

New Hampshire has a broad range of river types. The forested White Mountains contain many small non-alluvial headwater channels such as the upper Pemigewasset River that serve as the origin to some of New England's larger rivers. On the other end of the spectrum, larger meandering rivers such as the Merrimack downstream of Manchester, New Hampshire typically flow through more developed lands. The Piscataqua River is a small coastal drainage that discharges directly to the Atlantic Ocean. The wide range of river types, historic river corridor alterations, watershed land use change, and existing infrastructure makes river management in New Hampshire a challenge. The management of river systems in mountainous parts of New England is further complicated because incised channels downstream of steep terrain typically cannot access their floodplains during high flows to dissipate energy so severe instream erosion occurs. This issue may only be compounded if the trend of more frequent large precipitation events observed over the past 100 years in New England continues. Increased risk, repeated loss of human investments, and costly on-going river management is evident by events such as the recent flooding in October of 2005 that damaged substantial state and personal property, and which the U.S. Federal Government declared a major disaster in the State of New Hampshire. The use of natural process-based river assessment and restoration at the appropriate spatial scales can help identify and alleviate some risk to human investments in the river corridor, in addition to improving aquatic habitat. A river restoration guidelines document is a critical first step towards accomplishing these important goals and allowing for more effective management.

5.2 Glacial Influence

At the height of the "Great Ice Age" approximately a million years ago the Labrador Ice Sheet made its way south, completely covering New Hampshire and the rest of New England as far south as Long Island (Chapman, 1974). The sheet of ice topped Mount Washington by at least 1000 feet, thus providing enormous erosive force for underlying dislodged rock and soil particles to scour river-formed V-shaped valleys into glacier-formed U-shaped valleys (i.e., Franconia, Crawford, and Pinkham Notches). The glaciers not only formed major river valleys such as the Connecticut, but also formed lake basins such as the Winnipesaukee where weaknesses in bedrock existed.

The glaciers that moved south through New England had a profound lasting effect on the landscape with their retreat north as the climate warmed about 40,000 years ago (Chapman, 1974). Rivers from melting glaciers deposited tons of gravel and cobbles filling some valleys, while large glacial lakes deposited layers of silt and clay in other valleys. Rivers that flow through today's New Hampshire landscape continue to erode, transport, and re-deposit these glacial sediments, and attempt to do so in a dynamic equilibrium. This important 'paraglacial' (Church and Ryder, 1972) characteristic of rivers in formerly glaciated terrain is critical to consider when attempting restoration activities in the river corridor. Features such as sediment size and load, erodability of bed and banks, channel profile and planform can all be linked back to the glacial origins of the river valley. Human disturbances in the river corridor impede the flow of water and sediment from mountain to coast, disrupting the processes that began with the melting of the glaciers.

5.3 New Hampshire River Corridors and their Management

5.3.1 Mountain Sources

Mountain chutes tend to serve as sources for material due to land erosion in steep terrain and rapid export. The naturally straight, confined nature of streams in mountains leads to a lot of power in the active channel. Rock chutes and large boulders are typically found along the boundaries of headwater mountain streams and thus lateral erosion is minimal. The management of mountain streams is really a catchment, or small watershed, issue. Forestry operations and other forms of land use change in mountainous areas can lead to excessive sediment loads moving downstream. Mountain catchments can be quite sensitive to land use change. For example, small logging operations can lead to the creation of channel networks in locations where only overland flow was once present, initiating changes in headwater and downstream hydrology. Recent research has created mechanisms for assessing various physical aspects of mountainous streams such as hydraulic geometry (Wohl et al., 2004), channel classification (Montgomery and Buffington, 1997), and dominant discharge (Torizzo and Pitlick, 2004).

5.3.2 Alluvial Fans

River corridor management is often most complicated in the highly dynamic location where streams exit steep mountain terrain, such as at the perimeter of the White Mountains. As the channel slope abruptly flattens, water velocity decreases and large quantities of sediment are deposited in features called alluvial fans. The coarse, post-glacial sediment that has only had minimal shaping remains mostly unconsolidated and is highly mobile. Substantial bed movement is common at alluvial fans even during just moderate flood events (Pelletier et al., 2005). Because these locations can mark the most upstream location that development is possible given the presence of flatter terrain, human investments are sometimes unfortunately placed near alluvial fans. This sets the stage for conflict between natural form and process and human investments in the river corridor. Furthermore, upstream watershed land use change can lead to even more volatile conditions around alluvial fans. The high risk associated with alluvial fans warrants extreme management tactics that may include the purchase of endangered property, moving structures, and extraordinarily large set-backs.

5.3.3 Mid-Order Transport Streams

Medium-sized streams just out of the mountain steeps mostly transfer sediment (Schumm, 1977; FISRWG, 1998). In New England, mid-order streams have experienced many direct alterations. Historical channel straightening was used to clear snags to allow for floating logs. Small dams were built to use flowing water to provide mechanical power for mills. Railroads and roadways were placed in floodplains since the river had already started the work carving out easements. As human investments in the river corridor became more numerous, natural processes had to be curtailed to limit risks. Many New England river channels were regularly cleared and straightened to reduce roughness and increase flow conveyance so that low lying areas would no longer flood. Disconnection from the floodplain really was the pivotal point in time where management against natural process was determined, and thus rivers became not only sources of goods and services, but high risks and costs to society as well. With the increasing likelihood of more frequent and larger floods taking place in New England over the past century, historically degraded channels are likely to be incising at a more rapid rate reducing the remaining means of flow attenuation and sediment storage. River restoration towards natural processes seems to be the best chance of breaking out of the costly management of medium-sized river surrounded by human investments.

5.3.4 Large Alluvial Rivers

Sediment moved from mountain headwaters and transported through medium-sized streams tends to accumulate in depositional features in large meandering rivers before eventual watershed export. River corridors in these broad downstream valleys are frequently developed for agriculture or urban land uses, and often show broad impacts due to removal of natural vegetation and the cumulative effects of upstream channel changes. For example, local instability in the form of channel braiding may result from large slugs of sediment moving into larger rivers due to accelerated upstream delivery from the watershed or increased instream erosion. In addition to the physical impairment, reduced water quality is common in developed lands due to excessive loading of items such as nutrients and bacteria, and thermal modification. Large hydroelectric or flood control dams are also significant sources of impairment on larger rivers, greatly altering habitat.

5.3.5 Land Use Change and Current Infrastructure

The dominant land cover in New Hampshire is regenerating forests that have been maturing since the widespread harvest approximately 100 years ago to clear the way for traditional family agriculture. Timber harvest continues today at a relatively small rate for wood products; however, large tracts of land managed as working forests and farms are changing ownership and development is taking place in the form of residential, commercial, and associated land use types. Much of this development takes place in river corridors.

Transportation networks and pockets of urbanization complicate the present day river management scenario in New Hampshire. Parts of many of the State's roadways, such as State Route 302 along the Ammonoosuc River, are situated in valleys very close to active channels (Figure 5.1). River adjustment or blockage can lead to the costly loss of human investments. Transportation infrastructure complicates natural process restoration. Investments in urban areas close to streams, such as in Hanover, New Hampshire along the Connecticut River creates a host of threats to streams. In addition to the structures, roadways, and utility easements in the river corridor, short circuiting of stormwater runoff often causes channel instability and overall habitat degradation. "Sensible use of

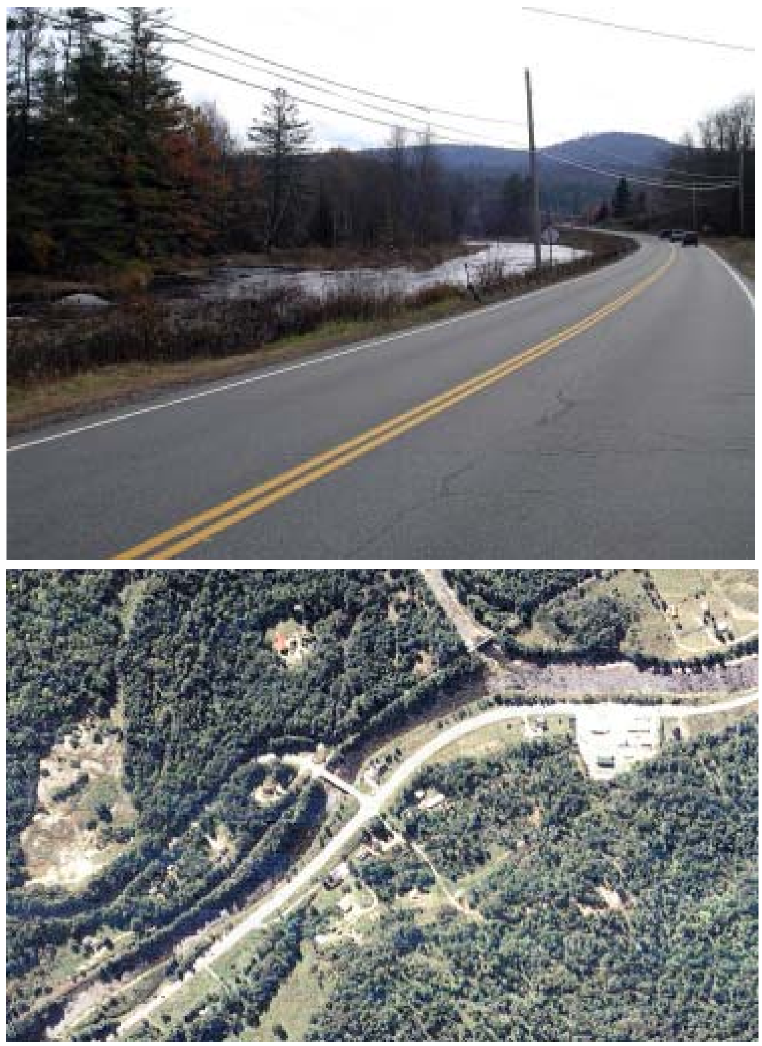


Figure 5.1: Photographs of State Route 302 and the Ammonoosuc River in Lisbon, New Hampshire (Source: Ray Lobdell, Ammonoosuc River Corridor Advisory Committee and Town of Littleton, Rivers Management Advisory Committee Presentation, April 12, 2006).

the river corridor and lands throughout the watershed helps to protect the river and ensure our enjoyment of its bounty. We recognize and can measure the impacts of different land uses on rivers. For example, impervious areas such as parking lots and buildings increase the volume and velocity of runoff, which in turn increases erosion. Runoff from impervious areas can carry with it road salt, oil, gasoline, anti-freeze, and other pollutants. Agricultural, residential and recreational developments have the potential to degrade waters with sediments, nutrients, pesticides and herbicides" (NHDES, 1997). Process-based restoration at the watershed scale allows for better understanding of channel stability and biotic potential in disturbed areas.

5.4 River Restoration in the New Hampshire Landscape

The broad types of channels, history of instream and land use alteration, and human investments in the river corridor necessitate a flexible yet consistent approach to river restoration in New Hampshire. A key issue is managing the conflict between human investments in the river corridor and natural river processes. The alteration of natural process and the attempts of a channel to return to equilibrium have been on-going in the State of New Hampshire and previously documented in detail (Yearke, 1971).

> *"Because flooding along the Peabody River in New Hampshire undermined a section of roadway, the river channel was relocated (manmade) in that section. The Peabody River was shortened by approximately 850 feet and its alignment straightened by this change. A small side stream was diverted to flow in the opposite direction. Immediately after construction, the channel began to rapidly seek its hydraulic gradient through erosion and scour. Its adjustment was a continuing process with major change occurring within the first year and adjustments of decreasing significance occurring each year thereafter. The original channel had an average fall of 52 ft/mi and the relocated channel was steepened to 80 ft/mi. The channel adjusted itself 75 ft/mi after two years and to 70 ft/mi seven years after construction. A channel cannot tolerate a severe gradient increase; thus, the upstream end of the channel degrades and the downstream end fills to overcome the man-made restructuring."*

Comprehensive restoration planning can lead to the application of appropriate design methods at relevant spatial scales to reduce risk and meet project goals. Presently the State of New Hampshire has several tools to support stream restoration activities. Provisional regional hydraulic geometry curves (see Figure 2.4) assist with sizing created channels based on drainage area. The utility of the regional curves will increase as more river measurements are added to the data set, which may eventually allow stratification by geomorphic channel type. For Federal and State funded projects taking place in the State of New Hampshire, a *Generic Quality Assurance Project Plan for Stream Morphology Data Collection* (Sweeney and Simpson, 2003) is available to assist with data collection techniques and promote consistent methods. These tools will be incorporated into the future guidelines in some capacity.

River restoration guidelines will serve as a valuable tool to design and install effective components that help accomplish the objectives of river restoration programs. From mountain headwaters to coastal rivers, the guidelines document will present a framework that will lead to more accurate project understanding and appropriate design. The anticipated selection mechanisms to pinpoint the appropriate design tools to be used for given project type and scope will ultimately lead to more standardized and effective implementation.

5.5 Conclusion

From small mountain headwaters to large coastal rivers, the diversity of river channel types in New Hampshire necessitates a wide range of river restoration design approaches. Standardized design guidelines must be flexible enough to address the many river restoration scenarios encountered, which are a function of project type, river characteristics, watershed location, and more. A particular management challenge in mountainous regions is the highly dynamic alluvial fan deposition areas where steep channels transition to more gradual slopes. Furthermore, confined river corridors filled with infrastructure such as roadways and utilities create conflicts between natural process and human investments leading to costly and risky management. Documented historic and recent damage associated with flooding in the State of New Hampshire illustrates the current need for revisiting river management methods and compiling standardized river restoration principals and guidelines.

6.0 CONCLUSION

This white paper reviews the central topics of natural channel form and process (Chapter 2.0), river system alteration (Chapter 3.0), river restoration (Chapter 4.0), and issues related to river restoration in the State of New Hampshire (Chapter 5.0). Spatial and temporal scale are key aspects of river structure and function, and the ability to properly identify disturbances and perform restoration at the appropriate scales is a major factor that determines the success of projects. At the root of impairment to the river corridor is the alteration of the balance between sediment and water. This equilibrium is fundamental for understanding change and rehabilitating natural process, and a useful foundation for investigating geomorphic variables, channel classification, and channel evolution models.

Historic and on-going threats to rivers originate within the river corridor and contributing watershed. The river restoration community is presently seeking ways to break out of mismanagement cycles that utilize temporary fixes that typically work against natural processes to respond to crises such as large floods. These activities have repeatedly proven to be costly, risky, and ultimately ineffective over the long-term. Land use change, existing infrastructure, and increasing magnitude and frequency of storm events complicate current river management efforts.

Channel construction and streambank stabilization are common components of restoration programs used to rehabilitate natural process and form. The goals of self-sustaining resiliency, ability to monitor desired improvements, interdisciplinary recovery, adaptive management, and expansion of natural process are critical to river restoration efforts. Analytical, empirical, and analog design tools are available for river restoration, and there is a recent move towards combined approaches to draw on the strengths of each.

Some existing manuals and documents present river restoration planning procedures; however, standardized design guidelines are more difficult to create given the inherent differences between every project site. A more comprehensive planning process to better understand a project is the first step towards design standardization. We advocate classifying the type of constructed channel or other practice based on geomorphic characteristics to create a clear vision of project constraints and potential, appropriate design tools, and human dimensions. This framework, combined with other selection charts for guiding specific types of project, will help organize the abundant existing river restoration information making it readily accessible for design.

Readers interested in exploring a topic covered in this white paper in further detail are directed to the reference library that contains important works that establish a topic, contain a comprehensive description, present theory, and explore application (Appendix A). In addition, information on the existing manuals on streambank stabilization, channel design, the technical aspects of river restoration, roadways and river corridor, monitoring, and river restoration policy guidelines may be obtained in the annotated bibliography (Appendix B) and the accompanying electronic document library.

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APPENDIX A: SELECTED FLUVIAL GEOMORPHOLOGY, STREAMBANK STABILIZATION, NATURAL CHANNEL DESIGN, AND RELATED REFERENCES (LAST UPDATED 5/8/06)

The following collection of references constitutes a selection of important papers and recent research covering topics related to fluvial geomorphology, streambank stabilization, and natural channel design. The amount of research taking place in these fields has greatly expanded over the past century making a comprehensive literature survey in all of the disciplines impractical and beyond the scope of this work. Nevertheless, the selected seminal works[1], general concept papers[2], technical theory documents[3], application reports and manuals[4], and reviews[5] listed here provide detailed information on the key principals of various aspects of fluvial geomorphology and how they are applied during natural channel design and streambank stabilization projects. An understanding of the fundamentals of the physical aspects of river systems (i.e., fluvial geomorphology, sediment transport, hydraulic geometry, dominant discharge, meander formation, stream channel classification, stream channel evolution, streambed movement, and streambank stability) will increase the likelihood of planning, designing, and installing successful stream rehabilitation projects where natural dynamics have been altered to achieve overall restoration goals.

Within each subject table references are listed in chronological order, and thus seminal works tend to appear first while application and review papers are at the end of the list. Superscripts indicate reference type, where multiple numbers are listed in decreasing order of applicability. For example, a superscript of "5,2,3" would indicate a review paper that covers general concepts and a little bit of theory. A superscript of "3,2" would signify a mostly theoretical paper with some general concept presentation.

Reference Type
[1]Seminal work
[2]General concept
[3]Technical theory
[4]Application
[5]Review

Fluvial Geomorphology

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Wallerstein, N. P. and C. R. Thorne, 2004. Influence of Large Woody Debris on Morphological Evolution of Incised, Sand-Bed Channels. Geomorphology 57(1-2):53-73. [4,2]

Reference Type
[1]Seminal work
[2]General concept
[3]Technical theory
[4]Application
[5]Review

APPENDIX B: ANNOTATED BIBLIOGRAPHY OF EXISTING MANUALS AND GUIDELINES ON STREAMBANK STABILIZATION, NATURAL CHANNEL DESIGN, AND STREAM RESTORATION (UPDATED 5/8/06)

Streambank Stabilization

Federal Government

A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization (Eubanks and Meadows, 2002)
http://www.fs.fed.us/publications/soil-bio-guide/

A comprehensive guide on planning and implementing soil bioengineering that includes detailed specifications on application techniques. The watershed/stream interaction is emphasized to help understand how reach-scale projects might best be designed and what effects might occur. The connection between upland and stream, the riparian ecosystem, is addressed in depth to frame the importance and challenges of the stabilization of streambanks. The use of an interdisciplinary team is advocated to increase the odds of reaching the desired future condition, which must be clearly identified at the outset of the project. Useful design specifications are presented, along with an example of monitoring forms. A recommended monitoring timeline is presented that should be performed for all projects to increase the chances of meeting project goals. Well-documented case studies offer sound project guidance. The guide concludes with an instructive listing of bioengineering techniques, each of which includes purpose, application, construction guidelines, inert materials list, installation directions, and photographic examples. Plant lists and blank field forms are located in the appendices.

Chapter 16 of the Engineering Field Handbook: Streambank and Shoreline Protection (NRCS, 1996)
http://wildfish.montana.edu/manuals/EFH-Ch16.pdf

Covers structural, soil bioengineering, and vegetation of streambanks. This document offers restoration planning and design guidance, in addition to detailed specifications of a variety of streambank protection techniques. Dimensions and installation recommendations are presented for many of the popular soft and hard bank stabilization methods. Appendix A contains the Isbash methodology to determining riprap size and Appendix B has a regional plant list to be used for revegetating streambanks.

Effects of Riprap on Riverine and Riparian Ecosystems (Fischenich, 2003)
http://el.erdc.usace.army.mil/wrap/pdf/trel03-4.pdf

Evaluates the environmental impacts associated with riprap applications for streambank stabilization. Riprap has mixed effects on aquatic organisms, with the majority of coldwater applications leading to impacts and most warmwater applications being beneficial. The discrepancy is likely a function of many factors (e.g., existing habitat and riprap specifications), and thus potential impacts on biological communities must be addressed on a site-by-site basis. The effects of riprap on stream function also vary. Riprap alters stream morphologic evolution by reducing or eliminating lateral stream migration and prevents riparian plant succession. Riprap has limited impacts on the hydrologic balance, with the exception of the chance for increased local water surface elevations due to near-bank velocity reduction and backwatering. Sediment dynamics tend to be altered by riprap application where local scour and deposition are frequently encountered and persist for various lengths of time after installation. Riprap can improve habitat by offering underwater interstitial voids for macroinvertebrates and juvenile fish, however, in many instances the loss of bank and riparian vegetation reduce cover and terrestrial food inputs. Water quality impacts of riprap are presumed to be minor. Some construction specifications are given for stone size, revetment dimensions, deflectors, the incorporation of vegetation, grade control, and sound installation procedures.

State Government

Integrated Stream Protection Guidelines (Cramer et al., 2002)

This document published by the Washington State Aquatic Habitat Guidelines Program reviews current scientific thinking on streambank protection, site/reach assessments to identify mechanisms of problems and possible solutions, project selection options, and the techniques used to protect streambanks. WA state agencies are applying the guidelines for fish habitat improvement, nonpoint source pollution reduction, a tool for hydraulic project review, methods for mitigation of streambank effects associated with highways, and general watershed recovery work. The descriptions of the processes important to understanding local and reach modes of bank failure is helpful for thinking of how the present conditions evolved and how one might go about a streambank rehabilitation project. When considering a solution to a problem, factors such as overall objectives, risk and cost, habitat needs, scale of impacts, and adaptive management are important. Project type selection matrices are presented that help match solutions with problems. Finally, the detailed accounting of streambank protection techniques contains a description, application notes, effects, design considerations, biological considerations, potential risk, construction considerations, cost, maintenance and monitoring. Appendices are included that cover relevant theory on hydrology, hydraulics, geomorphology. The guiding principals of the Washington Aquatic Habitat Guidelines Steering Committee that published this document are very useful over-arching principals that have broad application to stream rehabilitation projects and the concept of system restoration. The guiding principals accurately incorporate current scientific thinking on important natural processes, an understanding of the relationship between humans and water resources, and holistic goals of stream work.

Streambank and Shoreline Protection Manual (LCSMC, 2002)
http://www.co.lake.il.us/planning/pdfs/StrmManual.pdf

This document is largely a slimmed down version of the Chapter 16 in the NRCS Engineering Field Handbook (NRCS, 1996). Assessment, project selection, and design options (vegetative versus structural) are presented, along with specifications of selected practices. A useful table linking practice type to both where it is applicable and the problem addressed help guide streambank stabilization.

Streambank Revegetation and Protection: A Guide for Alaska (Walter et al., 2005)
http://www.sf.adfg.state.ak.us/sarr/restoration/techniques/images/reveg%20manual%20lo.pdf

This document offers useful technical details on proven revegetation and bioengineering techniques from stream restoration projects in Alaska. Lists of pointers to enhance growth of vegetation and rapid bank stabilization are given.

Guidelines for Streambank Restoration (GASWCC, 2000)
http://gaswcc.georgia.gov/vgn/images/portal/cit_1210/60/20/31110081Guidelines_Streambank_Restoration.pdf

A booklet published by the Georgia Soil and Water Conservation Commission to assist riparian land owners with erosion prevention and streambank restoration. The document is geared towards addressing small-scale projects, and offers lists of project steps and advice. Specification sheets for common bioengineering practices are supplied. Part of the information, writing, and images for the document were produced by Robbin B. Sotir & Associates.

Bioengineering for Hillslope, Streambank and Lakeshore Erosion Control (Franti, 1996)
http://ianrpubs.unl.edu/Soil/g1307.htm

This document contains a qualitative overview of bioengineering history, techniques, and application. A section on improving the odds of successful projects gives pointers on application.

Non-profit

A Citizen's Streambank Restoration Handbook (Firehock et al., 1995)

This Izaak Walton League publication offers an overview of stream processes and basic application techniques to streambank stabilization. The background, rough design details, and planning information are useful for projects that are small in size and scope.

‘Natural Channel Design’

Federal Government

Channel Restoration Design for Meandering Rivers (Soar and Thorne, 2001)
http://wildfish.montana.edu/manuals/Channel_Restoration_Design_for_Meandering_Rivers.pdf

A U.S. Army Corps of Engineers technical guidance document for the design of stream channels based on a multidisciplinary method primarily combining traditional hydraulic engineering and principals of fluvial geomorphology (i.e., the ‘geomorphic engineering approach’). The document promotes channel restoration design that results in a stable geometry that is self-sustaining for the given flow and sediment dynamics. An in-depth historical review of both the engineering and geomorphology approach to channel design is presented, along with fundamental theory of both fields. The document has a detailed discussion of the channel-forming flow. A confidence band is used in channel design, and suggests that there is no exact solution to hydraulic geometry, longitudinal slope, and sinuosity in restored channels and that the stream will adjust towards a new equilibrium if allowed to do so. Channel and planform geometry are ultimately determined from sediment transport characteristics, and equations are give for restoration design that considers the morphological context and traditional engineering methodology.

State Government

Guidelines for Natural Stream Channel Design for Pennsylvania Waterways (KST, 2002)
http://www.keystonestreamteam.org/kst_documents.htm#NSCDGuidelines

This document offers a sound overview of natural stream channel design, including technical information on project planning, design, and implementation. The fundamental philosophy employed is to "work with, not against, a stream’s natural form and function." Rosgen’s method is recommended, where a reference reach is used as a template for restoration. It is suggested that an interdisciplinary team be used to cover all aspects of the stream. Projects must be addressed on a case-by-case basis. Key aspects are community, data, design, permitting, consultants, construction, and monitoring. A nice overview of working with stakeholders to achieve both a common view of what is to take place and acceptance amongst partners and regulators is presented. Each of the design methods of analog (reference reach), empirical (fundamental data sets), and analytical (hydraulic design) are touched upon. The key concept of bankfull dimension and discharge is presented given its importance in the restoration design. Permitting is covered at both the state and federal levels, and Pennsylvania’s "phased project" approach is described to spread permitting time and costs throughout the course of the project. Thorough sections on how to hire a qualified consultant and how to proceed with construction are presented. Finally, a brief mention of monitoring is given.

Stream Restoration: A Natural Channel Design Handbook (Doll et al., 2003)
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html

A manual created in the State of North Carolina promoting the methods and techniques associated with natural stream channel design. The document largely draws on the Rosgen assessment methodologies including variables measured and classification system used. The document contains a very useful section on options for restoring an incised stream channel, a situation frequently encountered in temperate regions with historic channel management. A useful presentation of regionalizing the natural channel design process is presented throughout the document in the form of hydraulic geometry relationships, gauge data, reference conditions, and sample projects. Such assessment work is recommended in other states and regions where a lot of stream restoration is likely.

Stream Restoration Technical Information

Federal Government

Stream Corridor Restoration: Principals, Processes, and Practices (FISRWG, 1998)
http://www.nrcs.usda.gov/technical/stream_restoration/newtofc.htm

This report is an extensive manual covering stream corridor theory and analysis, hydrology and hydraulics, geomorphic processes, chemical characteristics, biology, stability, disturbance, restoration planning, project design and implementation, and adaptive management of restoration projects. The interagency manual is widely used in the United States to guide stream restoration education and the different phases of project planning. Although design details are beyond the scope of this document, the planning information presented is critical to the creation of successful projects.

DRAFT Stream Restoration Design Handbook (NRCS, 2005)

This manual, which is nearing completion, is the next step after the Stream Corridor Restoration manual referenced above. The former Interagency Manual offers the necessary tools for project planning, while this NRCS document offers guidance on project design. "This handbook presents engineering and ecological assessment and design tools that are applicable to a wide range of stream restoration work, whether it primarily follows natural stream restoration approaches or is strictly a structural project. The focus of this handbook is on the "how-to"."

Hydraulic Design of Stream Restoration Projects (Copeland et al., 2001)
http://wildfish.montana.edu/manuals/Hydraulic_Design.pdf

This U.S. Army Corps of Engineers document is a manual of the hydraulic design of stream restoration projects. Hydrology (frequency analysis, flow duration curves, channel forming discharge, and stormwater), stability (geomorphology and hydraulic geometry), and hydraulic design (geomorphology, hydraulic parameters, planform, sediment, operation and maintenance, quality control, and implementation and monitoring) are all covered in detail. The manual offers important equations and guides the reader to the appropriate analytical tools to perform design tasks. Specific consideration is given to engineering design amongst physical constraints while attempting to maintain naturally stable stream channels.

Channel Stability Assessment for Flood Control Projects (USACOE, 1994)
http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-1418/entire.pdf

This is a guidance document that addresses the instability in floodways due to discharge and sediment regime. Traditional practices are covered (e.g., channel cleanout and enlargement) rather than natural channel design. However, the stability evaluation and design chapters offer useful input to natural channel design, with reference to both hydraulic engineering design and geomorphic principals. The document contains some useful nomagraphs (e.g., mean flow velocity versus bed material grain size, p. 5-5) that are useful for establishing quick design guidelines.

Channel Rehabilitation: Processes, Design, and Implementation (Watson et al., 1999)
http://chl.wes.army.mil/library/publications/ChannelRehabilitation.pdf

This Army Corps of Engineer document presents a planning process, theory on geomorphology, a description of channel modification activities, and the fundamentals of engineering design for stream channel rehabilitation. Although an interdisciplinary approach is advocated, the document is mostly a comprehensive guide on the physical engineering aspects of stream work. The appendix covering the determination of effective discharge, an essential but often unused variable due to challenging determination, is very useful for the initial assessment and phases of design.

Stream Channel Reference Sites: An Illustrated Guide to Field Technique (Harrelson et al., 1994)
http://216.48.37.142/pubs/20753

This document constitutes a ‘compact field manual’ that is used to identify and investigate reference reaches to use as templates for stream restoration. It contains an entry-level review of survey, site observation, hydrology, hydraulics, sediment transport, and quality control information necessary to describe reference reaches. It is a useful primer on field measurement techniques and should be carried in the field for those just getting started with stream investigations.

State Government

Generic Quality Assurance Project Plan for Stream Morphology Data Collection (Sweeney and Simpson, 2003)
http://www.des.state.nh.us/WMB/Was/QAPP/

This document contains a generic QA Project Plan (QAPP) for grant projects funded through the New Hampshire Department of Environmental Services using EPA Clean Water Act section 319 funds that involve stream morphology data collection. The document offers a template for the steps in typical stream restoration projects, including problem identification, project tasks, minimum standards, documentation, useful existing data, field measurement methods, and reporting.

Stream Habitat Restoration Guidelines (Saldi-Caromile et al., 2004)
http://wdfw.wa.gov/hab/ahg/shrg/index.htm

This State of Washington document offers a comprehensive overview of stream processes, and stands out as one which clearly discusses the dynamic nature of streams that include disturbance regimes and recovery cycles. A key part of creating diverse habitat that can support a broad range of organisms is flow diversity. Connectivity in the longitudinal, lateral, and vertical dimensions is also essential and often overlooked during rehabilitation. This manual is process-focused and thus sets a good foundation for creating sound restoration plans. The assessment chapter mentions all the relevant scales (watershed – site) and even addresses the fact that the term watershed can encompass many scales based on who is using the term. Some examples of watershed assessments used in WA are given. The extensive chapter on developing a restoration strategy links fundamental river processes to enhancement, rehabilitation, and restoration planning. A concise presentation of the differentiation between each of these distinct terms is presented, as is a recommended set of goals and objectives for each. Emphasis is always given to passive restoration and the goal of restoring both form and process at all relevant scales. The implementation stage of restoration includes identifying stakeholders, project constraints, goals and objectives, design criteria to meet goals, necessary data, and risk. Only then are the final design, plans, and technique drawings created, and the project implemented. Finally, effectiveness monitoring is a necessary part of the project. Detailed review of popular rehabilitation practices are given and include a description, anticipated effects, application notes, comments on risk, design methods, permitting, construction considerations, cost estimate, monitoring plan, and examples. In the channel modification sub-section, the three design camps: 1. analog (reference reach), 2. empirical (universal data sets), and 3. analytical (engineering design) are mentioned. A combination of these offers a good check on design. A list of twelve variables that may be used in channel modification design are presented as an iterative process to create the right size channel to move sediment and water in equilibrium. Of most interest here is the inclusion of designing for channel migration and sediment transport along a rehabilitated reach. Monitoring is addressed, and a plan should be established to ensure that outcomes are definitively known. The review of streambank stabilization is mostly left for the WA Integrated Streambank Protection Guidelines. Theory on important aspects of aquatic ecosystem (e.g., fluvial geomorphology and sediment transport) is presented in the appendices.

California Salmonid Stream Habitat Restoration Manual (Flosi et al., 2002)
http://www.dfg.ca.gov/nafwb/manual.html

This manual covers assessment, habitat restoration, and other pertinent information with a focus on restoration of salmon and steelhead. Watershed and habitat assessment are covered, with a comprehensive naming system on 24 habitat types with schematics describing each. This convention seems to be a useful way to identify habitat with regards to its fisheries potential. A study indicated that a 10% random sample still generates accurate estimations of what is present over a reach. The project implementation part of the manual has a good library on instream habitat enhancement methods. The part on fish passage at stream crossings presents a useful way to identify good and bad fish passage sites, and label question able sites for further hydraulic analysis using FishXing. Data tables of helpful inputs on fish behavior are supplied. A part on upslope assessment and restoration is currently under revision. The final part of the manual discusses the importance of riparian habitats and their restoration. A library of plantings for California is presented. The Appendices offer useful supplemental information and a completed habitat assessment report is presented as a guide to using the protocols discussed in the manual.

Maryland's Waterway Construction Guidelines (MDE, 2000)
http://www.mde.state.md.us/Programs/WaterPrograms/Wetlands_Waterways/documents_information/guide.asp

This technical guidance document presents design details of common traditional and bioengineering practices employed in the alteration and restoration of streams. A brief introduction presents the fundamentals of design velocity (Manning's) and shear stress, yet little design process information is given. For each practice, a description, effective uses and limitations, material specifications, installations guidelines, and a detailed sketch are presented.

Vermont Stream Geomorphic Assessment Protocol Handbooks: Remote Sensing and Field Surveys Techniques for Conducting Watershed and Reach Level Assessments (VTANR, 2004)
http://www.anr.state.vt.us/dec/waterq/rivers/htm/rv_geoassesspro.htm

These handbooks consist of a comprehensive three phase physical assessment of streams. Phase 1 is a watershed level information gathering protocol where maps and windshield surveys are used to collect data. Phase 2 consists of a rapid field assessment where key variables are measured along selected reaches to get a more detailed understanding of stream geomorphology. Finally, phase 3 is a survey level field component where precise data are collected. The State of Vermont maintains a database management system for entry of standardized data to offer publicly available information on stream condition when watershed planning and management activities are taking place. Although these protocols are not directly used for design and implementation of restoration activities, the data generated using these protocols are useful for stream restoration design and would certainly enhance the chances of implementation of successful projects.

Adaptive Management of Stream Corridors in Ontario and Natural Hazards Technical Manual (OMNR, 2001)
http://www.trentu.ca/wsc/pub_adaptiveman.shtml

This CD-ROM created by the Ontario Ministry of Natural Resources, and the result of a large collaborative effort amongst regulators, practitioners, and academics, is an interdisciplinary guide to stream management. It is rooted in geomorphology, engineering and ecology, and thus offers important information on natural channel design, including an adaptive management methodology. In attempting to develop a comprehensive design concept, this document is based on the theory of protecting what is healthy and rehabilitating what is not. A nice comparison of the differences between natural systems and non-natural designs is presented. In the first version of this document, OMNR stated goals of natural channels to be physically stable, biologically self-sustaining, and overall self regulating. This document does a good job early on distinguishing between the management options of restoration, rehabilitation, enhancement, and protection, which are often confused. A clear picture showing the physical jurisdiction of regulatory agencies and needed permits clearly illustrates the potential permitting process in stream restoration. The section on the effects of land use on streams offers some nice overviews of potential impacts associated with European settlement and present day watershed activities. An informative review of stream processes, form, and function is presented with several nice data tables for easy reference. The planning and design process is laid out well in a qualitative manner, however the one change I would consider is to formulate the monitoring plan prior early in the design phase after the initial assessment so it is in place before project implementation. An extensive bibliography is presented in the appendices covering up to 1999.

Non-profit

Urban Subwatershed Restoration Manual No. 1: An Integrated Framework to Restore Small Urban Watersheds (Schueler, 2004)

This manual constitutes the first of a series of eleven presently being produced by the Center for Watershed Protection addressing a variety of aspects in the restoration of small urban watersheds. The manuals cover an integrated restoration framework (1), restoration planning (2), stormwater retrofits (3), stream repair practices (4), riparian management (5), discharge prevention (6), pervious area management (7), pollution source control (8), municipal practices (9), the Unified Stream Assessment (10), and the Unified Subwatershed and Site Reconnaissance (11). Presently, manuals 1, 2, 4, 8, 10, and 11 are available. Although these manuals focus on urban stream restoration, the principals and practices set forth in each may also pertain to other land use settings. The content of these manuals has been used to develop many community-based restoration plans and projects.

Roadways and River Corridors

Federal Government

River Engineering for Highway Encroachments: Highways in the River Environment (Richardson et al., 2001)
http://isddc.dot.gov/OLPFiles/FHWA/010589.pdf

This manual is the authoritative document on hydraulics around highways, bridges, and other roadway infrastructure. Theory on river processes is presented so that an understanding in order to offset lateral bank erosion and streambed changes is obtained. In depth theory on open channel flow, alluvial channels, sediment transport, river morphology, bed and bank stabilization, and bridge scour are given. Application features such as data needs to design crossings design examples are given. Although this manual is quite advanced in technical content, many nomagraphs are presented to guide users through design phases.

Design Charts for Open Channel Flow (FHWA, 1961)
http://www.fhwa.dot.gov/engineering/hydraulics/pubs/hds3.pdf

"This publication contains charts which provide direct solution of the Manning equation for uniform flow in open prismatic channels of various cross sections; instructions for using the charts; a table of recommended values of n in the Manning equation, and tables of permissible velocities in earth and vegetated channels; instructions for constructing charts similar to those presented; and a nomograph for use in the solution of the Manning equation."

Hydraulic Design of Highway Culverts (Normann et al., 1985)
http://isddc.dot.gov/OLPFiles/FHWA/009342.pdf

This document offers detailed information for the design of new culverts and improving existing ones. Based on principals of hydrology and hydraulics, this manual is useful for assisting river rehabilitation projects where road crossings are present.

Drainage of Highway Pavements (Johnson and Chang, 1984)
http://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec12.pdf

"This edition of Hydraulic Engineering Circular No. 12 incorporates new design charts and procedures developed from laboratory tests of interception capacities and efficiencies of highway pavement drainage inlets. The text includes discussion of the effects of roadway geometry on pavement drainage; the philosophy of design frequency and design spread selection; storm runoff estimating methods; flow in gutters; pavement drainage inlets, factors affecting capacity and efficiency, and comparisons of interception capacity; median inlets; embankment inlets; and bridge deck inlets. Five appendixes are included with discussion of the development of rainfall intensity-duration-frequency curves and equations, mean velocity in a reach of triangular channel with unsteady flow, the development of gutter capacity curves for compound and parabolic roadway sections, and the development of design charts for grates of specific size and bar configuration."

Design of Roadside Channels with Flexible Linings (Kilgore and Cotton, 2005)
http://www.fhwa.dot.gov/engineering/hydraulics/pubs/05114/05114.pdf

This manual contains design procedures for four major categories of flexible lining: vegetative linings; manufactured linings; riprap, cobble, gravel linings; and gabion mattress linings. Design procedures for composite linings, bends, and steep slopes are also provided. The design procedures are based on the concept of maximum permissible tractive force. Methods for determination of hydraulic resistance applied shear stress as well as permissible shear stress for individual linings and lining types are presented.

Hydraulic Design of Energy Dissipaters for Culverts and Channels (FHWA, 1983)
http://isddc.dot.gov/OLPFiles/FHWA/010492.pdf

This manual offers background and design guidance for dissipating energy at culverts and in open channels. The first five chapters provide theory and background to utilize the design criteria and guidance in chapters six through eleven. Topics such as hydraulic jumps, drop structures, and riprap are covered.

Evaluating Scour at Bridges (Richardson and Davis, 1995)
http://www.fhwa.dot.gov/bridge/hec18SI.pdf

This document "presents the state of knowledge and practice for the design, evaluation, and inspection of bridges for scour." It covers theory and evaluation of bridge scour, and creates an understanding of susceptibility to undermining and instability.

Bridge Scour and Stream Instability Countermeasure (Lagasse et al., 1997)
http://www.fhwa.dot.gov/bridge/hec23.pdf

"This document provides guidelines for the selection and design of appropriate countermeasures to mitigate potential damage to bridges and other highway components at stream crossings. A countermeasure matrix is presented as an aid to identify most types of countermeasures which have been used by State highway agencies for bridge scour and stream instability problems. The matrix supports the selection of appropriate countermeasures considering such characteristics as the functional application, suitable river environment, and estimated allocation of maintenance resources. In addition, SHAs with installation experience and design guideline references are included for each type of countermeasure. Design guidelines for the following seven countermeasures are provided based on information obtained from SHAs: bendway weirs/ stream barbs, soil cement, wire enclosed riprap, articulated concrete block systems, articulating grout filled mattresses, Toskanes, and grout filled bags. Design Guideline 8 presents guidance for pier and abutment riprap protection from Hydraulic Engineering Circular 18."

Stream Stability at Highway Structures (Lagasse et al., 1991)
http://www.fhwa.dot.gov/bridge/hec20.pdf

"This document provides guidelines for identifying stream instability problems at highway stream crossings for the selection and design of appropriate countermeasures to mitigate potential damages to bridges and other highway components at stream crossings. The HEC-20 manual covers geomorphic and hydraulic factors that affect stream stability and provide a step-by-step analysis procedure for evaluating stream stability problems. Guidelines and criteria for selecting countermeasures for stream stability problems are summarized, and the design of three countermeasures spurs, guide banks, and check dams) is presented in detail. Conceptual design considerations for many other countermeasures are summarized."

State Government

Fish Habitat Manual: Guidelines and Procedures for Watercourse Crossings in Alberta (TRANS, 2001)
http://www.trans.gov.ab.ca/Content/doctype123/production/fishhabitatmanual.htm

This guidance document for the province of Alberta Canada informs project designers of the regulatory process for making changes to streams, as well as guides both government and non-government workers in the process of design and application of stream alteration. The introduction offers a nice layout of project type and permitting requirements, and supplies a roadmap for project design. Each of the chapters contains background information, for example Chapter 8 contains the fundamentals of geomorphic channel design. A good definition of a stable channel is presented – "a stable channel is one that has neither a net deposition nor net erosion of channel substrate in the long term." Rosgen's methods are described, yet some interesting other design criteria of channels are given. Where possible, the active channel should convey only up to the 2-yr storm while larger events fill the floodplain to maintain connectivity. Low flow is addressed, where depths of 0.2 m are called for throughout a stream for 7Q2 ('habitat maintenance flow'), in critical reaches for 7Q10 ('local extinction flow'), and in over-wintering pools for 7Q20 ('system extinction flow'). This is a useful presentation of low flow bottlenecks that are often a part of some aspect of stream restoration. A simple listing of 9 design steps is give: define design objectives, define existing conditions, define expected natural regime, identify inconsistencies, design parameters for unconstrained site, identify constraints, identify tradeoffs, develop final design, and evaluate the design. This procedure is nicely laid out as it mentions the intuition often used by practitioners while rapidly sifting through project design. Other chapters of this manual are quite useful as well, and the appendices contain detailed specification sheets on rehabilitation practices. Each description includes applicability, advantages, limitations, design and implementation, maintenance, and further readings.

Massachusetts River and Stream Crossing Standards: Technical Guidelines (MARSCP, 2006)
http://www.streamcontinuity.org/pdf_files/MA_Crossing_Stds_3-1-06.pdf

This document develops performance standards for culverts and other stream crossing structures for the Commonwealth of Massachusetts. The guidelines were created based on review of existing methods and data of road crossings in rivers. The guidelines seek to meet the goals of fish and aquatic organism passage, river continuity, and wildlife passage. A "stream simulation" approach is used where ecosystems, rather than individual species, are target for design and restoration efforts.

Maine Fish Passage Policy & Design Guide (MEDOT, 2004)
http://mainegov-images.informe.org/mdot/interagency-meetings/iameet/april2004/documents/Fish_Passage_Policy_2004_Draft.pdf

This document develops a policy and design process for fish passage for the State of Maine. Both bridges and culverts are addressed, and a goal of both resource protection and effective highway management at water crossings exists throughout the document. Goals of river crossings include replicating natural flows, passing large floods, and protecting life cycle functions in an economical way.

Monitoring

Federal Government

DRAFT Stream Restoration Design Handbook (NRCS, 2005)

Chapter 16 of this draft manual presents an approach to project monitoring that is framed in the adaptive management process. Recommendations for monitoring variables, methods, and response for popular practices are given. Of the little material available on monitoring, this manual offers a relatively large portion of information useful for application.

Stream Corridor Restoration: Principals, Processes, and Practices (FISRWG, 1998)
http://www.nrcs.usda.gov/technical/stream_restoration/newtofc.htm

Chapter 6 of this manual offers guidance on monitoring and evaluating project effectiveness. A discussion of monitoring objectives is given, rather than specific methods.

State Government

Guidelines for Natural Stream Channel Design for Pennsylvania Waterways (KST, 2002)
http://www.keystonestreamteam.org/kst_documents.htm#NSCDGuidelines

Chapter 9 of this manual offers a short monitoring recommendation for pre- and post- monitoring associated with channel creation. A recommendation is given to "Define monitoring parameters to match your objectives and make sure your objectives are both achievable and measureable."

Stream Restoration: A Natural Channel Design Handbook (Doll et al., 2003)
http://www.bae.ncsu.edu/programs/extension/wqg/sri/stream_rest_guidebook/guidebook.html

Chapter 12 of this manual offers a brief introduction to effectiveness monitoring and project evaluation. Several physical parameters such as grain size and channel shape and water temperature are recommended for monitoring.

Stream Habitat Restoration Guidelines (Saldi-Caromile et al., 2004)
http://wdfw.wa.gov/hab/ahg/shrg/index.htm

Technical Appendix 29 offers guidance on establishing a monitoring plan for evaluating aquatic habitat. This information can be applied to restoration effectiveness determination. The document also contains a discussion on variables to monitor for a given project goal, as well as how to respond and facilitate the adaptive management process based on gathered data.

California Salmonid Stream Habitat Restoration Manual (Flosi et al., 2002)
http://www.dfg.ca.gov/nafwb/manual.html

Part eight of this manual covers evaluation and monitoring. Topics covered include pre-project monitoring, monitoring upon project implementation, and evaluation of fish habitat enhancement structures.

Stream Restoration Qualitative Reports and Policy Papers

Federal Government

Principals for the Ecological Restoration of Aquatic Resources (USEPA, 2000)
http://www.epa.gov/owow/wetlands/restore/principles.html#4

List of guiding principals formulated by the Watershed Ecology Team of the Office of Wetlands, Oceans, and Watersheds of the U.S. EPA that have been found to be essential to the success of aquatic restoration projects. The principals are: Preserve and protect aquatic resources; restore ecological integrity; restore natural structure; restore natural function; work within the watershed/landscape context; understand the potential of the watershed; address ongoing causes of degradation; develop clear, achievable and measurable goals; focus on feasibility; use reference sites; anticipate future changes; involve a multi-disciplinary team; design for self-sustainability; use passive restoration, when appropriate; restore native species, avoid non-native species; use natural fixes and bioengineering; and monitor and adapt where changes are necessary.

Guidelines for Instream Habitat Restoration Projects (USFWS, 2000)
http://www.r6.fws.gov/pfw/PDFiles/instream.pdf

This document is a Region 6 U.S. Fish and Wildlife Service (USFWS) guidance document that endorses the use of Leopold's "bankfull discharge concept" during instream habitat projects. Specifically, a recommendation is made to only use bank hardening techniques at or below bankfull depth and have projects screened by a Rosgen-trained (i.e., Wildland Hydrology) morphologist. A naturally table channel is the most important design goal of all instream restoration.

Policy on Streambank Stabilization Projects (USFWS, 2001)
http://www.r6.fws.gov/pfw/PDFiles/bankersos10threv.pdf

A Region 6 U.S. Fish and Wildlife Service (USFWS) guidance document endorsing concepts of naturally stable channels when reviewing or designing bank stabilization projects. The document advocates the Rosgen classification system to promote consistent reporting of steam types and condition. The emphasis here is the Mountain-Prairie Region of USFWS. The importance of riparian habitat is discussed, as well as allowing continual tree recruitment of riparian species. A suggestion is made that hard materials are not used on streambanks unless they are rapidly eroding (i.e., several lateral feet every year). Guidance for this document was also obtained from Stream Corridor Restoration: Principals, Processes, and Practices (FISRWG, 1998).

State Government

Oregon Aquatic Habitat: Restoration and Enhancement Guide (OPSW, 1999)
http://wildfish.montana.edu/manuals/habguide99-complete.pdf

A guide to restoration and enhancement in Oregon that gives qualitative details of each activity used to improve stream condition. Each practice has a description, regulatory requirements, guidance and considerations, and agencies offering technical assistance. The permitting component both in the practical descriptions and particularly in the section on state and federal agencies is quite useful for planning restoration activities.

Internal Technical Guidelines for Stream Restoration (NCDENR, 2001)
http://h2o.enr.state.nc.us/ncwetlands/streamgd.doc

This document guides staff of the North Carolina Department of Environment and Natural Resources on stream restoration. The guide is largely qualitative, yet contains several very useful components to design and review of projects. First, a flow chart of potential federal and state permits (p. 5) guides the project team and reviewer through the permitting process. Also, a stream work check list (p. 29) for project designers helps increase the odds of both addressing all of the needs of the regulatory community and producing a successful project.

Restoration of Urban Streams (Kelly, 2001)
http://www.state.nj.us/dep/watershedmgt/DOCS/Restoration%20of%20Urban%20Streams.pdf

This short document used by the State of New Jersey consists of a qualitative overview document of urban stream restoration issues. Table 3 is useful as it presents NRCS cost estimates (per unit length or area) of common stream rehabilitation practices used in stream restoration programs.

Erosion and Sediment Controls for Riparian Areas (STOPPP, 2000)
http://www.flowstobay.org/pdfs/bmp/Construction%20Series/streambroch.pdf

This (draft) pamphlet offers information on erosion and sediment controls for riparian areas to be used in San Mateo County, California. The goal is to inform streamside land owners of best management practices. Such a pamphlet on one sheet could be useful to offer brief guidance to citizens and links to regulatory agencies that perform and guide stream restoration.